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Ontario Geological Survey
Open File Report 6100

Summary of Field Work and Other Activities 2002

2002

Ontario

ONTARIO GEOLOGICAL SURVEY

Open File Report 6100

Summary of Field Work and Other Activities 2002

edited by

C.L. Baker, E.J. Debicki, R.I. Kelly and J.R. Parker

2002

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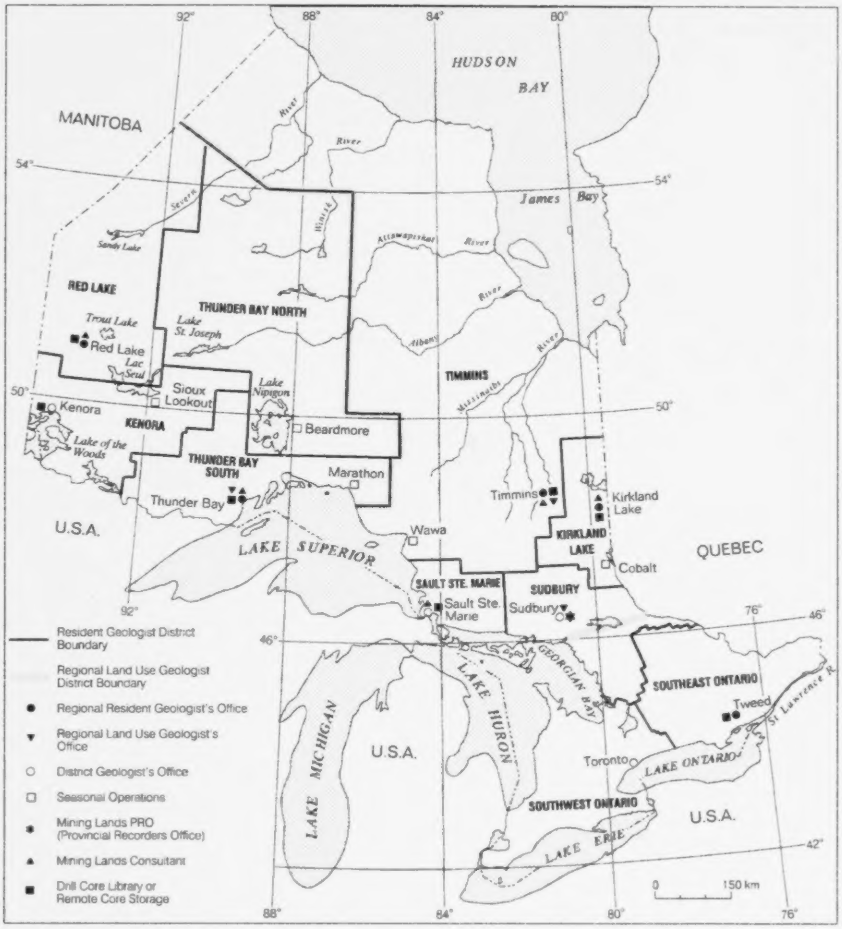
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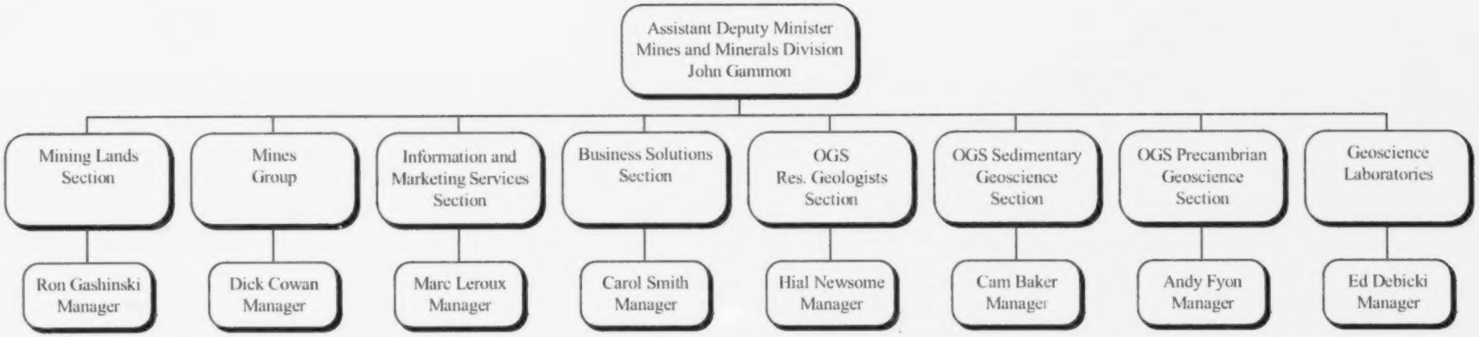
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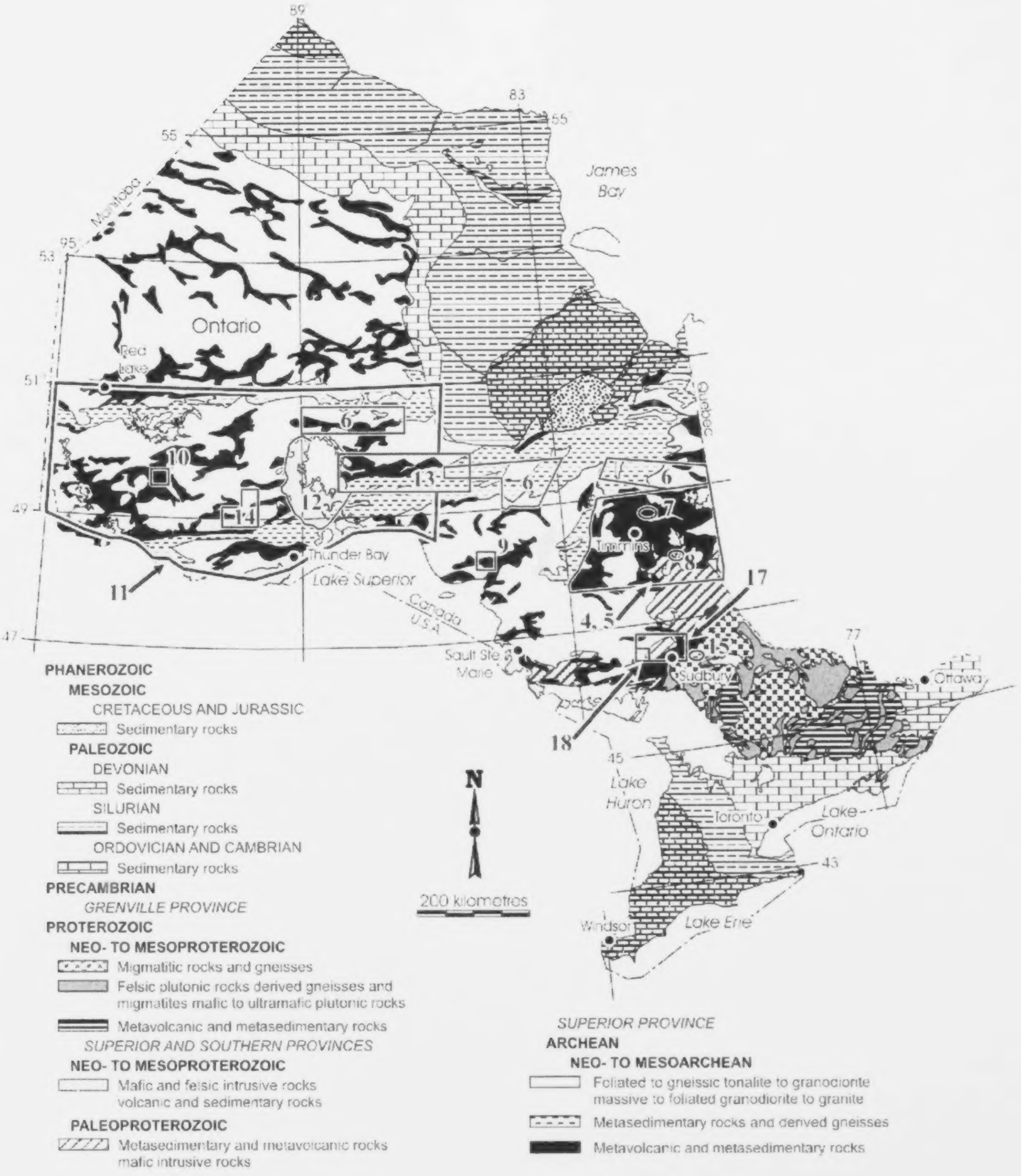
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Sedimentary rocks
SILURIAN
Sedimentary rocks
ORDOVICIAN AND CAMBRIAN
Sedimentary rocks
PRECAMBRIAN
GRENVILLE PROVINCE
PROTEROZOIC
NEO- TO MESOPROTEROZOIC
Migmatitic rocks and gneisses
Felsic plutonic rocks derived gneisses and migmatites mafic to ultramafic plutonic rocks
Metavolcanic and metasedimentary rocks
SUPERIOR AND SOUTHERN PROVINCES
NEO- TO MESOPROTEROZOIC
Mafic and felsic intrusive rocks volcanic and sedimentary rocks
PALEOPROTEROZOIC
Metasedimentary and metavolcanic rocks mafic intrusive rocks
SUPERIOR PROVINCE
ARCHEAN
NEO- TO MESOARCHEAN
Foliated to gneissic tonalite to granodiorite massive to foliated granodiorite to granite
Metasedimentary rocks and derived gneisses
Metavolcanic and metasedimentary rocks

Location of Precambrian Geoscience Section project areas. Numbers correspond to article numbers.

1. Precambrian Geoscience Section – Program Overview

J.A. Fyon

Precambrian Geoscience Section, Ontario Geological Survey

GOAL AND RESPONSIBILITY OF THE PRECAMBRIAN GEOSCIENCE SECTION

The goal of Precambrian Geoscience Section (PGS) is to improve the understanding of the Precambrian geology of Ontario and mineral deposit settings and to convey this knowledge to clients through multi-year, multidisciplinary studies to address critical geological problems, in key geographic areas.

PGS is responsible for

- mapping of Ontario's Precambrian bedrock and understanding of various mineral deposit settings
- regional gravity, magnetic and electromagnetic geophysical data and derivative products in support of the bedrock mapping program

PROGRAM DIRECTION: STRATEGIC THRUSTS

Core Bedrock Mapping and Geophysics Program

The PGS program is organized into several technical or administrative strategic thrusts (Table 1.1):

- understand the geology and metallogeny of high mineral potential areas in the Superior, Southern and Grenville provinces.
- understand and inventory provincial-scale relationships, settings and descriptive data sets of commodities or deposits types currently of interest to the mineral exploration industry (e.g., potential diamond-bearing rocks, gold mineralization, rare-element and/or petalite-bearing pegmatites, nickel-copper-platinum group element (PGE) mineralization and volcanogenic massive sulphide mineralization (VMS)).
- improve knowledge of, and access to, geophysical information by providing an effective and efficient information management system through the identification, recovery, (re-)formatting, organization and delivery of all available OGS and proprietary geophysical information; and provide derivative geophysical products, concepts and ideas, based on those geophysical data, to support the bedrock mapping program.
- implement program support practices and instruments to address and refine the PGS core program, the human resource strategy, digital data standards, measurement of program results and impact and program management practices.
- provide liaison role, representation, or support on behalf of the Mines and Minerals Division, the OGS, and PGS on committees, boards, meetings, or program needs.

Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.1-1 to 1-7.

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These strategic thrusts are addressed through a series of initiatives, built upon one or more projects (Parker, this volume). The purpose of the strategic thrusts is to focus the skilled staff and resources in key geological areas to address the priorities and needs of the initiative.

To complement existing PGS staff skills and capacity, the PGS program is complemented by a series of collaborative projects, or "partnerships", with universities, other governments, and industry (*see also* Parker, this volume).

Table 1.1. Strategic thrusts of the Precambrian Geoscience Section: 2001 to 2002 and beyond.

STRATEGIC THRUST	OBJECTIVES	KEY INITIATIVES
Core Bedrock Mapping and Geophysics Program		
Understand the geology and metallogeny of high mineral potential in the Superior, Southern, and Grenville provinces	a) Improve understanding of geology and mineral potential of key geographic areas that have not been mapped recently or that are inferred to contain important geological relationships, through systematic mapping and compilation at scales of 1:20 000, 1:50 000 and 1:100 000 b) Improve understanding of distribution of old and young crust that influence metallogenic patterns in western Superior Province c) Document the setting of, and controls on, platinum-palladium mineralization related to Proterozoic rocks d) Compile and interpret government and private sector regional airborne geophysics to enhance understanding of bedrock geology and mineral potential of the a) exposed Sachigo Subprovince; b) Proterozoic substrate to Hudson Bay Lowland; and Archean substrate to James Bay Lowland	Western Superior Province: NATMAP, Lithoprobe Lake Nipigon Region Geoscience Initiative Abitibi Initiative Proterozoic Initiative Geology and metallogeny of northwest Ontario initiative Sudbury Targeted Geoscience Initiative
Understand and inventory provincial-scale relationships, settings and descriptive data sets of commodities or deposits types currently of interest to the mineral exploration industry (e.g., potential diamond-bearing rocks, gold mineralization, rare-element and/or petalite-bearing pegmatites, platinum group element mineralization (PGE) and volcanogenic massive sulphide mineralization (VMS))	a) Improve understanding of, and mineral potential for, diamonds b) Improve understanding of, and mineral potential for, volcanic-associated, base-metal mineralization by documentation of the distribution of FII- to FIII-type felsic metavolcanic rocks across the Superior Province c) Improve understanding of, and mineral potential for, fertile peraluminous granites and related rare-element and industrial mineral (e.g., petalite) pegmatite mineralization d) Improve understanding of, and mineral potential for, magmatic Ni-Cu-PGE mineralization associated with mafic to ultramafic intrusions and komatiitic flows e) Improve understanding of geological history and metallogeny of Proterozoic rocks in the Grenville and Southern provinces f) Improve understanding of geology and controls on magmatic Ni-Cu-PGE mineralization in the Sudbury Igneous Complex, Nipissing mafic intrusions, and Early Proterozoic mafic intrusions g) Update and maintain geochronology database	Provincial-scale metallogenic inventory initiative Provincial-scale diamond assessment initiative Provincial-scale pegmatite mineralization initiative Magmatic nickel-copper-PGE metallogeny of Ontario initiative

Table 1.1. Continued

STRATEGIC THRUST	OBJECTIVES	KEY INITIATIVES
Core Bedrock Mapping and Geophysics Program, continued		
Improve knowledge of, and access to, geophysical information by providing an effective and efficient information management system through the identification, recovery, (re-)formatting, organization and delivery of all available OGS and proprietary geophysical information; and provide derivative geophysical products, concepts and ideas, based on those geophysical data, to support the bedrock mapping program	a) Provide on-going support of bedrock mapping and compilation projects b) Develop new approaches, procedures and methodologies to integrate and establish geophysical component of bedrock mapping projects using NSWGS practices as a model c) Assess and apply new technologies for processing, interpreting and presenting geophysical data, such as "worming" technology for interpretation of gravity data and Red Lake hyperspectral survey with Canadian Centre for Remote Sensing d) Complete, post (to OGS web-site) and maintain a Geophysical Atlas containing a graphical index of all available geophysical information in Ontario e) Establish on-line repository (master archive) of all available geophysical information which will be used to seed all publications of geophysical data and which will be maintained by the OGS geophysicist f) Supervise contract work to reprocess and level airborne geophysical data to Ontario master grid datum to produce relevant derivative digital g) Reformat and upgrade ERLIS airborne geophysical data sets from old formats to the current OGS standard h) Implement and develop rock properties database as part of OGS bedrock mapping projects, i.e., recover rock density data; magnetic susceptibility data; specific gravity; establish data standards, storage format and plan i) Acquire proprietary, multi-parameter, regional airborne geophysical survey data	Geophysics and Bedrock Mapping Integration Initiative Geophysics and Rock Properties Data Set Initiative
Implement program support practices and instruments to address and refine the human resource strategy, digital data standards and program management practices	a) Complete the design and documentation of the digital mapping tools, standards, and documentation b) Continue the implementation of program planning, project management, human resource plans, and impact tracking practices, processes, tools, and databases	Core program and specific projects
Provide liaison role, representation, or support on behalf of the Mines and Minerals Division, the OGS, and PGS on committees, boards, meetings, or program needs	a) Provide executive assistant support for OGS Advisory Board and its Technical Committee b) Provide support for planning sessions involving regional client associations c) Committee of Provincial Geologists d) National Geological Surveys Committee e) Board of Directors of Mineral Exploration Research Centre, Laurentian University f) Commissioner, North American Commission on Stratigraphic Nomenclature g) Precambrian-at-Large Representative, Joint Technical Program Committee, Geological Society of America	

Table 1.1. Continued

STRATEGIC THRUST	OBJECTIVES	STATUS
Add-on Geoscience Projects: Operation Treasure Hunt		
Contract and project management of airborne geophysical projects	Close carry-over Operation Treasure Hunt projects a) Overall project management b) Procure proprietary airborne geophysical data c) Provide and supervise QA/QC inspection services of airborne geophysical data	Service provided by Paterson, Grant & Watson Limited; Stephen Reford is OTH Geophysicist
Complete data processing and release of new airborne geophysical surveys over areas having mineral potential	Acquire new time domain electromagnetic, magnetic, and gamma-ray spectrometric data over the Fort Hope greenstone belt and purchase proprietary airborne geophysical survey data from industry	Operation Treasure Hunt airborne geophysical survey data products under development
Precambrian bedrock compilation	a) Conducted over central Superior and Southern provinces b) Compliments on-going Grenville, Abitibi, and western Superior Province mapping and compilation efforts	
Add-on Geoscience Project: Ontario Mineral Exploration Technology Program		
Administrative partnership with Mineral Exploration Research Centre, Laurentian University	a) Techniques to find mineral resources in bedrock beneath conductive or thick overburden. These conditions are common throughout northern Ontario b) Methods to "see" through the Paleozoic rocks to explore for mineral resources, including diamonds, in the underlying Precambrian rock of the Hudson Bay and James Bay lowlands c) Effective ways to utilize Ontario's Quaternary geology to explore for mineral resources buried in the bedrock	Delivery by OMET Program Office, Mineral Exploration Research Centre, Laurentian University (Rayner, Lafleur and Fyon, this volume)
Add-on Geoscience Project: Lake Nipigon Region Geoscience Initiative		
Participate in the initiative on the Implementation Committee, the Technical Committee, and the project level	Ontario Prospectors Association is lead agency having received a $3.5M conditional award from Northern Ontario Heritage Fund Corporation	Project planning in progress

Geoscience Projects

During fiscal year 2002 to 2003, the PGS supported 33 active core projects and 30 active collaborative projects (Parker, this volume).

FIRST NATION DIALOGUE

The Precambrian Geoscience Section continued its dialogue with First Nation communities and related Tribal Councils where there is a common interest in present and future geoscience projects. These discussions involved Treaty 3 and Treaty 9 First Nation communities.

The purpose of the dialogue is to develop shared understandings of respective needs and expectations related to resource development and geological survey projects. With one First Nation community, the dialogue will culminate in a formal communication agreement.

PROJECT PLANNING, MANAGEMENT, AND CONSULTATION PROCESS

To plan and deliver 63 active geoscience projects, delivered by core staff and in collaboration with our partners, PGS management and staff continued to refine the planning and project management processes and practices. Information required to describe projects, monitor and adjust progress, and assess their impact on the minerals industry is collected and analyzed to assess if program goals are met (e.g., Churchill and Fyon 1999; Churchill et al. 2000; Churchill et al. 2001).

To formulate and discuss project plans for summer of 2002 and to begin development of summer 2003 project plans, PGS staff were involved in several consultations with regional client associations:

1. July 2002: Ontario Geological Survey Advisory Board Technical Committee in Sudbury
2. July 2002: Northwest Ontario Prospectors Association in Thunder Bay
3. July 2002: Joint meeting with Northern Prospectors Association and Porcupine Prospectors and Developers Association in Matheson
4. October 2002: Ontario Geological Survey Advisory Board
5. October 2002: Southern Ontario Prospectors Association, Tweed

ADD-ON PROGRAMS

PGS staff collaborated with other OGS staff to formulate and deliver 2 significant add-on geoscience programs:

- Operation Treasure Hunt (OTH) projects are being brought to closure and a preliminary assessment of the impact of the OTH geoscience program was conducted (Fyon, Churchill and Baker, this volume).
- Ontario Mineral Exploration Technologies Program (Rayner, Lafleur and Fyon, this volume)

PGS staff continued to participate on the Discover Abitibi! Technical Committee.

PGS staff also participated on the Implementation Committee and the Technical Committee for the Lake Nipigon Region Geoscience Initiative.

INTER-JURISDICTIONAL AND COMMITTEE REPRESENTATION

During the 2002 to 2003 fiscal year, PGS staff represent the Ontario Geological Survey on several inter-jurisdictional committees and associations, including

1. Committee of Provincial Geologists
2. National Geological Surveys Committee
3. Mineral Exploration Research Centre, Laurentian University, Board of Directors
4. Lithoprobe Western Superior Transect liaison
5. Commissioner, North American Commission on Stratigraphic Nomenclature (until November 2002)
6. Precambrian-at-Large Representative, Joint Technical Program Committee, Geological Society of America
7. Adjunct professor at Carleton University, University of Ottawa, or Laurentian University.

ONTARIO GEOLOGICAL SURVEY ADVISORY BOARD

The Ontario Geological Survey Advisory Board provides client-focussed, expert strategic advice and guidance to the Minister of Northern Development and Mines on

- issues facing, and that must be addressed by, the minerals industry;
- the needs and priorities of the minerals industry; and,
- major program priorities of the OGS to guide OGS in meeting its core business of providing the province's geological data and mapping function.

PGS provides executive support to the OGS Advisory Board and its geoscience Technical Committee. During the past year, the OGS Advisory Board and its Technical Committee met several times.

NEW FACES TO THE PRECAMBRIAN GEOSCIENCE SECTION

D. Rainsford joined the PGS in August 2002 accepting a short-term contract as PGS geophysicist.

L.A.F. Hall remained in the PGS as the project geologist for a one-year project to revisit geological relationships in Ogden Township and initiate bedrock mapping south of Timmins in Deloro Townships. She has recently accepted a permanent Geoscientist position with PGS.

C.A. Macdonald continued to work with the PGS to complete the Operation Treasure Hunt project to study and inventory platinum group element (PGE) mineralization and mafic to ultramafic intrusions in Ontario under the leadership of C. Vaillancourt.

J.B. Selway continued to work with the PGS to complete an Operation Treasure Hunt project to study fertile peraluminous granites and related rare-element pegmatite mineralization in Ontario under the leadership of F.W. Breaks.

E. Roy returned to PGS in September 2002, accepting a short-term contract as PGS drafter.

MINISTRY OF NORTHERN DEVELOPMENT AND MINES P.R.A.I.S.E. AWARD

In 2001, the Ministry of Northern Development and Mines launched its People Recognition Award In Service Excellence (P.R.A.I.S.E.) to formally recognize ministry staff who contribute to improvements in service, operations, and work environment. Awards are presented for both individual (*"You Made a Difference Award"*) and team-oriented achievements (*"Partnership Award"*). P.R.A.I.S.E. expresses our collective appreciation to staff for their efforts in helping to contribute to the success of the ministry.

In October, 2002, Dr. Fred Breaks was awarded a P.R.A.I.S.E. award to recognize his contributions under the *"You Made a Difference Award"*. This award recognizes employees who demonstrated outstanding accomplishments, performance and exemplary behaviour in areas of improving service, operations and/or the work environment, leadership, innovation, valuing people, and teamwork.

For his outstanding efforts, Dr. Michael Easton was awarded a P.R.A.I.S.E. Certificate of Achievement under the *"You Made a Difference Award"* for his long-standing contributions to provincial, national, and international geoscience community and to the science.

Norm Trowell received a P.R.A.I.S.E. Certificate of Achievement under the *"You Made a Difference Award"* for his long-standing contributions to Health and Safety issues and committees on behalf of the OGS field staff and the Mines and Minerals Division.

For their efforts as members of the Provincially Significant Mineral Potential Team, Ben Berger, Glen Johns, Tom Muir, Norm Trowell, John Ayer and Michael Easton were awarded a P.R.A.I.S.E. Certificate of Achievement.

The PGS is proud of its employees and the selfless contributions they all make to document the geology of Ontario and to communicate those results provincially, nationally, and internationally. The geological insight provided by all the PGS staff help ensure Ontario remains an attractive jurisdiction in which to invest.

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2. Precambrian Geoscience Section – Project Overview

J.R. Parker

Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

The fundamental core functions of Precambrian Geoscience Section (PGS) projects are to

1. provide geoscience maps, reports, data, technical talks and posters, new concepts and ideas and client consultations; and
2. provide regional airborne magnetic and electromagnetic geophysical data, derivative products, and concepts and ideas based on those geophysical data to support the bedrock mapping program.

In 2002, the PGS produced 11 Preliminary Maps, 10 Open File Reports, 13 Miscellaneous Release—Data (MRDs), 7 compilation maps and 69 airborne geophysical maps. Approximately 15 technical talks and 35 posters were presented at various geoscience forums throughout the year.

The program direction and strategic thrusts (Fyon, this volume) of the PGS address the mission statement and core business of the Ministry of Northern Development and Mines. Strategic thrusts are achieved through a variety of initiatives that are built upon one or more projects (Table 2.1). Therefore, project development, selection, planning and implementation are based on the strategic thrusts and initiatives in order to achieve alignment of individual projects with Ministry priorities.

The PGS presently has 33 active core projects (*see* Table 2.1). The PGS is also involved in 30 active collaborative project agreements in various stages of completion and with a variety of partners (Table 2.2). The collaborative project agreements include 10 active projects with the Geological Survey of Canada (GSC) (*see* Table 2.2). Four projects from the Operation Treasure Hunt initiative and the Phoenix Bedrock Mapping Project were carried over and completed in 2002. In all, the PGS supported 63 geoscience projects during the 2002–2003 fiscal year.

Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.2-1 to 2-10.

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Table 2.1. Precambrian Geoscience Section core projects, 2002–2003.

Initiative	Project	Project Goal	Project Status
Abitibi Initiative	Abitibi Compilation – Matachewan sheet	Complete 1:100 000 scale compilation of Abitibi greenstone belt	On schedule for completion in April 2003
	Discover Abitibi!	Participation in Technical Committee	On-going
	Regional mapping in the Matachewan area: Cairo and Alma townships	Map 6 townships and compile geology in Matachewan area	First year completed. Cairo and Alma townships mapped at 1:20 000 scale. Maps due in 2003
	Shining Tree synoptic report	Complete 1:50 000 scale compilation map and synoptic report	Map completed and report in preparation. To be published in 2003
	Bedrock mapping in the Timmins west area: Carscallen and Denton townships	1:20 000 scale bedrock mapping	Project complete. Map and report published in August 2002
	Bedrock mapping in the Timmins west area: Ogden Township	1:20 000 scale mapping to resolve geological problems in Ogden Township	Field work completed. Open File Report to be completed in 2003
	Bedrock mapping in the Timmins west area: Deloro Township	1:20 000 scale bedrock mapping of Deloro Township	Field work completed. Map due in 2003
Proterozoic Initiative	Geology of the Mazinaw and Palmerston Lake area	Write synoptic report	In progress, plan to complete in 2003
	Geology and mineral potential of Henry–Loughrin townships	1:20 000 scale bedrock mapping; complete synoptic report of River Valley area	Mapping complete by end of October 2002
	Lake Nipigon Region Geoscience Program	On-going participation in Implementation Committee and Science Committee	On-going
	Geological compilation of the Kawagama – Wilberforce areas	Digitize and publish 1:50 000 scale maps by S. Lumbers	Digitizing complete. Project on schedule for completion in 2003
	Geochemistry of Osler Group	Compile unpublished lithogeochemical data for Proterozoic volcanic rocks and intrusions	Project on schedule for release in 2002
	Reconnaissance of Nipigon sills and ultramafic intrusions	Reconnaissance and compilation of geology in Lake Nipigon region	Project complete
Metallogeny and Geology of Northwest Ontario	Geology of the Wabigoon area	Map Wabigoon–Dinorwic lakes area at 1:20 000 and 1:50 000 scales	Completed 3rd year of 5 year project; 2 maps schedule for release in April 2003
	Heaven – Garden – Lac des Iles synoptic report	Synoptic report to summarize 3 years of bedrock mapping	In progress and on schedule for release in 2003
	Phoenix Bedrock Mapping Project	1:50 000 scale bedrock mapping in Beardmore area (5 townships to map)	Complete. All deliverables published as of October 2002

Table 2.1. Continued

Initiative	**Project**	**Project Goal**	**Project Status**
Provincial-scale Metallogenic Inventory Initiative	Distribution of potentially VMS-productive felsic metavolcanic rocks	Compile locations of FI-, FII- and FIII-type rhyolites across Ontario	On-going compilation
	Characteristics of mineralized intermediate to felsic plutonic systems	Gather/compile information on barren and mineralized felsic plutons across Ontario	On-going compilation
	Update and maintain geochronology database	Maintain up-to-date geochronology database for Ontario	On-going. Last published in 2001
Provincial-scale Diamond Assessment	Kasabonika indicator mineral study	Indicator mineral study from till samples collected in the vicinity of the Kasabonika First Nation	Complete. Report published in October 2002
Geological Compilation Maps	Operation Treasure Hunt: 1:250 000 scale bedrock geology compilation maps	Complete 10 1:250 000 scale bedrock compilation maps	Four maps published. 4 to be published in 2003
Geophysics and Bedrock Mapping Integration Initiative	Fort Hope – New South Wales methodology	Apply NSW methodology to integrate geophysics with bedrock mapping	Delayed. Will progress in 2003
	Geophysics integration with bedrock mapping projects	Integrate geophysics into the PGS bedrock mapping program	On-going
	Geophysical training through interpretation of selected greenstone belts	Providing geophysical training to geoscientist to assist geophysicist.	On-going
Geophysics and Rock Properties Data Set Initiative	Rock properties project	Collect and archive rock properties data	OTH part of project is complete. On-going
	Geophysical data conversion	Reformat geophysical data from older formats	Reformatted data to be released in 2002
	Levelling and reformatting projects	Level airborne geophysical data to Ontario master grid	On-going and on schedule for completion
	Operation Treasure Hunt – Data Management	Manage and QC all OTH data	On-going. Completion in March 2003
	Fort Hope geophysical survey	Essentially complete with some final data processing	To be released in late 2002 or early 2003
Support and Program Management Practices	Attributed Maps (Smart Maps) synoptic mapping – Abitibi Subprovince and elsewhere	Release maps with data base attached	Suspended
	Digital map standards throughout Ontario	Standardize digital map standards	Suspended
	PGS Learning Plan – Administrative Project	Develop and commit to learning plan for PGS	On-going. Plan established for 2002–2003
Project and Results Management Initiative	Impact analysis of Operation Treasure Hunt geoscience projects	Analyze impact of OTH projects on economy of Ontario and mineral industry	On-going, but relatively complete
	Impact analysis of PGS mapping program	Analyze impact of geoscience projects on economy of Ontario and mineral industry	On-going
Methods Development and Data Standards Initiative	Integrated solution for field data collection and processing	Establish new methods for digitally collecting geological data in the field	Delayed. Progress to be made in fall/winter 2002–2003

PRECAMBRIAN GEOSCIENCE SECTION INITIATIVES

PGS initiatives are based on geographic or functional groupings and are made up of 1) team initiatives (i.e., Abitibi Initiative) consisting of individual projects that are designed to meet an overall goal; 2) inter-jurisdictional team initiatives, such as Western Superior NATMAP, that consist of individual and joint OGS and GSC projects that are also designed to meet an overall goal or objective; 3) individual, focussed projects. The major initiatives of the PGS are subdivided into 5 broad categories outlined below and in Table 2.1.

1. Initiatives that involve collaborative project agreements with the Geological Survey of Canada
    - Western Superior NATMAP and Lithoprobe focussed mainly in north and northwest Ontario;
    - Targeted Geoscience Initiative focussed on the Sudbury Igneous Complex (SIC);
    - The Far North Initiative in the Hudson and James Bay lowlands.
2. Initiatives involving provincial-scale metallogenic compilation and inventory studies
    - Documentation of pegmatite-hosted mineralization;
    - Documentation of magmatic nickel-copper-platinum group element (PGE) metallogeny in Ontario that includes projects such as the PGE mineralization and mafic to ultramafic intrusion compilation and inventory (collaborative project agreements between OGS and the Mineral Exploration Research Centre (MERC, Laurentian University) and GSC, respectively);
    - Diamond assessment;
    - Inventories of various tectonic settings relevant to mineral exploration.
3. Initiatives based on geographic area
    - Abitibi initiative;
    - Metallogeny and geology of northwest Ontario;
    - Proterozoic initiative.
4. Initiatives involving program support of the PGS program
    - Support and program management practices;
    - Project and results management;
5. Initiatives involving geophysical projects
    - Geophysics and bedrock mapping integration initiative
    - Geophysics and rock properties data set initiative.

Table 2.2. Precambrian Geoscience Section collaborative projects, 2002–2003.

Initiative	**Project**	**Project Collaborator**	**Project Progress**
Abitibi Initiative	Timmins West metamorphic study	P.H. Thompson Geological Consulting	Publication of report and map in 2002
	Physical volcanology of komatiites in Ontario	Mineral Exploration Research Centre, Laurentian University	MSc thesis study changed to PhD which extended project
	Holloway Township structural geology	University of Ottawa; Battle Mountain Gold; Barrick Gold Corp.	Thesis defense completed. Awaiting PhD thesis for Mines Library
	Matheson syenite project, Highway 101	University of Ottawa	MSc student is writing thesis
	Geochemistry and metallogenesis of komatiites in Ontario: compilation project	Mineral Exploration Research Centre, Laurentian University	Final report delayed in editing stage
	Geology, volcanology, lithogeochemistry, alteration associated with base metal mineralization in the Big Four Lake area, Shining Tree	University of Ottawa	MSc student is writing thesis
	Kenogamissi batholith structural study	University of Ottawa	In write-up stage.
	Geochemistry and tectonic evolution of Shining Tree area	Portsmouth University	Progress unknown. No communication from Portsmouth University.
	Timmins MEGATEM® II survey (Discover Abitibi! initiative)	FedNor (Industry Canada), Falconbridge Limited, Geological Survey of Canada	To be published in late 2002
	GIS and remote sensing applications in the identification of the location and spatial association of kimberlite in the Lake Timiskaming structure	D. Dempsey, G. Gionet	On-going
Proterozoic Initiative	Mid-Continent Rift compilation	United States Geological Survey; Minnesota Geological Survey; McAlester College; Wisconsin Geological and Natural History Survey	On-going
	Paleomagnetic discrimination of Proterozoic dike swarms east of Lake Nipigon	University of Toronto	On-going
Collaborative Projects with GSC: Sudbury Targeted Geoscience Initiative	Structural geology of southwestern Sudbury Igneous Complex (Trill, Drury, Fairbank and Denison townships)	University of Ottawa; Geological Survey of Canada	Final year for TGI. In write-up stage. Preliminary report to be published in 2002. Final report and map in 2003.
Collaborative Projects with the GSC: Far North Initiative	Reprocessing of ODM–GSC geophysics of exposed Archean in Sachigo Subprovince	Geological Survey of Canada	On-going, plan to complete in 2003
	Reprocessing of ODM–GSC geophysics of Proterozoic substrate, James Bay Lowlands	Geological Survey of Canada	On-going, plan to complete in 2003
	Reprocessing of ODM–GSC geophysics of Archean substrate, Hudson Bay Lowlands	Geological Survey of Canada	On-going, plan to complete in 2003

Table 2.2. Continued

Initiative	Project	Project Collaborator	Project Progress
Collaborative Projects with the Geological Survey of Canada (GSC): Western Superior NATMAP and Lithoprobe Initiatives	Structural and stratigraphic, metallogenic synthesis Red Lake greenstone belt	Geological Survey of Canada	Delayed due to slow progress on map completion by GSC
	Geology of east Sachigo Subprovince	Geological Survey of Canada	Complete. 1:250 000 scale map to be published in 2003
	Geology of south-central Wabigoon Subprovince	Geological Survey of Canada	Complete. 1:250 000 scale map due in 2002
	Geology of east Wabigoon Subprovince	Geological Survey of Canada	Complete. 1:250 000 scale due in 2002
	Regional metallogeny of northwest Superior Province	Geological Survey of Canada	On-going. Metallogenic maps to be published in late 2003 or early 2004
	Sm/Nd isotope study: correlation between central and east Wabigoon Subprovince	Geological Survey of Canada	Delayed, but on-going
	Western Superior Lithoprobe Transects: reflection seismic transect routes	Geological Survey of Canada and various universities	Suspended
Western Superior Lithoprobe Initiative	Structural controls on shear-hosted gold occurrences in the Beardmore–Geraldton Belt at the Quetico–Wabigoon subprovincial boundary	Laurentian University	Bedrock geology map published in 2002. MSc student completing thesis
	Winnipeg River project	K.Y. Tomlinson	Delayed. Progress to be made in 2003
Provincial-scale Pegmatite Mineralization	Fertile peraluminous granites and related rare-element pegmatite mineralization in Ontario	Open University	Complete. Report and MRD due in 2002
	Rare-metal mineralization and associated S-type fertile granitoids, northeast Ontario	Open University	Completed during summer 2002. Report in 2003
Metallogeny and Geology of Northwest Ontario	Volcanology and VMS-related alteration and mineralization of Marshall Lake, Archean felsic volcanic centre – eastern Wabigoon Subprovince	Laurentian University	MSc student writing thesis
Geophysics and Bedrock Mapping Integration Initiative	Hyperspectral survey: Red Lake greenstone belt	Canadian Centre for Remote Sensing	On-going
Documentation of magmatic nickel-copper-PGE metallogeny in Ontario	Geology, stratigraphy, chemostratigraphy, and ore mineralogy of the River Valley intrusion	Mineral Exploration Research Centre, Laurentian University	Data released. MSc student writing thesis
	Geology, stratigraphy, chemostratigraphy, ore mineralogy and metallogeny of Entwine Lake intrusion, Wabigoon Subprovince	Mineral Exploration Research Centre, Laurentian University	Map published in 2002. MSc student writing thesis
	Operation Treasure Hunt: Platinum group element inventory in mafic to ultramafic intrusions in Ontario	Mineral Exploration Research Centre, Laurentian University; Geological Survey of Canada	CD released in collaboration with GSC in March 2002. Final report and data release on schedule for publication in December 2002.

Collaborative Projects with the Geological Survey of Canada

Field work for the Western Superior NATMAP initiative was completed in 2000. In 2002, the PGS continued to work on two 1:250 000 bedrock compilation maps for release in December: 1) the east Wabigoon sheet encompassing the Onaman–Tashota terrane; and 2) the south-central Wabigoon sheet encompassing the Atikokan and Lumby Lake areas. A 1:250 000 map sheet for the east Sachigo Subprovince is scheduled for release in the spring of 2003. The PGS is also responsible for completing a series of 6 metallogenic compilation maps building upon the bedrock compilation maps. The Geological Survey of Canada (GSC) is responsible for delivering the western and north-central Wabigoon bedrock maps for release in December, 2002 as well as the east Uchi sheet in 2003.

One partnership project with Laurentian University was completed under the Western Superior Lithoprobe initiative to study structural controls on shear zone-hosted gold mineralization in the Beardmore–Geraldton Belt at the Quetico–Wabigoon subprovince boundary. A 1:10 000 scale bedrock geology map was published in 2002 (DeWolfe 2002) and the MSc thesis is currently being written. This project is supported under an Ontario Geological Survey – Laurentian University Graduate Mapping School Agreement. Interpretation of the Lithoprobe reflection seismic transect routes across the western Superior Province continued in 2002.

The Sudbury Targeted Geoscience Initiative (TGI) is a three-year program (2000–2003) designed to gain a better understanding of the setting and processes involved in forming the large nickel-copper-PGE deposits of the Sudbury Igneous Complex (Ames, this volume). The initiative consists of 4 collaborative projects that include the Geological Survey of Canada, the Ontario Geological Survey, mineral industry and several universities. One of these projects is an investigation of the lithological and structural controls on mineralization in the Sudbury Igneous Complex and in its immediate footwall (Dubois and Benn, this volume). This two-year project, supported under an Ontario Geological Survey – University of Ottawa Collaborative Project Agreement, has involved bedrock mapping in contiguous parts of Trill, Drury, Fairbank and Denison townships in the southwest part of the Sudbury Igneous Complex.

G.M. Stott commenced work on the geological interpretation of the Archean and Proterozoic substrate below the Phanerozoic cover of the James Bay and Hudson Bay lowlands and the exposed Archean in the Sachigo Subprovince as part of a Ontario Geological Survey – Geological Survey of Canada Collaborative Project Agreement. The interpretation will use reprocessed ODM–GSC airborne geophysical data and proprietary geophysical data purchased under the Operation Treasure Hunt initiative. The project will 1) compile geoscience data for the James Bay and Hudson Bay lowlands in order to provide an interpretation of bedrock features beneath the Phanerozoic cover; and 2) produce 3 1:500 000 scale geological maps in hardcopy and digital formats.

Provincial-Scale Metallogenic Compilation and Inventory Studies

The PGS continued a rare-element pegmatite characterization project to study rare-element mineralization. This is a continuation of an ambitious project, originally supported under the Operation Treasure Hunt initiative, to compile, document and study fertile peraluminous granites and related rare-element pegmatites across Ontario (Breaks, Selway and Tindle, this volume). The purpose of this project is the preparation of a comprehensive field, chemical, mineralogical and geochronological database for fertile granites and associated rare-element pegmatites for the entire Superior Province of Ontario. Field work in 2002 focussed on northeastern Ontario. Once again, several new and exciting exploration targets were identified (Breaks, Selway and Tindle, this volume).

Another ambitious project, supported by Operation Treasure Hunt, was initiated in 2001 to determine the potential for platinum group element mineralization in mafic to ultramafic intrusions across Ontario (Vaillancourt et al. 2001). The project is a collaborative effort between the PGS, the Mineral Exploration Research Centre (MERC, Laurentian University), and the Mineral Resources Division of the GSC. Lithogeochemical data generated during the Operation Treasure Hunt project was released on a CD-ROM that was co-published by the GSC and OGS in 2002 (Hulbert and Vaillancourt 2002). The CD also contains compiled information on known nickel-copper and platinum group element deposits in Ontario. Work on a final report and final digital data release continued into 2002.

Ongoing, multiyear, province-scale projects that fall under the initiative to create inventories of various tectonic settings relevant to mineral exploration are 1) the documentation and distribution of FII-type and FIII-type, potentially volcanogenic massive sulphide deposit (VMS-) productive felsic metavolcanic rocks; 2) the characterization of mineralized intermediate to felsic plutonic systems (Beakhouse, this volume); and 3) to update and maintain the geochronology database for Ontario. Denver Stone continued an ongoing kimberlite, base metal and gold indicator minerals study in the northern Superior Province (Stone 2002).

Initiatives Based on Geographic Area

The Abitibi initiative includes 7 core business, multiyear, mapping projects (*see* Table 2.1), including the 1:100 000 scale Abitibi compilation in the Matachewan area, as well as 9 collaborative project agreements (*see* Table 2.2) (Ayer, this volume). Staff continue to participate on the Technical Committee of the Discover Abitibi! initiative, which is a community-based and directed program designed to stimulate exploration for, and eventual development of, mineral deposits within the Abitibi greenstone belt of northeastern Ontario. The program will be achieved through the cooperation and collaboration between Federal, Provincial and Municipal governments and private-sector partners.

The geology and metallogeny of the northwestern Ontario initiative currently includes 3 projects: 1) geological mapping in the Dryden–Wabigoon area (Beakhouse, this volume); 2) completion of a synoptic report for the Heaven–Garden–Lac des Iles greenstone belts; 3) completion of the Phoenix Bedrock Mapping Project (Hart, terMeer and Jolette 2002); and 4) completion of a study of the geology, stratigraphy, chemostratigraphy, ore mineralogy and metallogeny of the Entwine Lake intrusion, Wabigoon Subprovince (Arnold 2002), which is also supported under an Ontario Geological Survey – Mineral Exploration Research Centre (MERC, Laurentian University) Collaborative Project Agreement.

The Proterozoic initiative includes several projects, such as 1) the geology of Henry and Loughrin townships, west of the River Valley area (Easton, this volume); 2) geological compilation (1:50 000 scale) of the Kawagama–Wilberforce areas in the Grenville Province; 3) geological and lithogeochemical reconnaissance of Nipigon sills and ultramafic intrusions in the Lake Nipigon area (Hart, this volume); 4) paleomagnetic discrimination of Proterozoic dike swarms east of Lake Nipigon, which is an Ontario Geological Survey – University of Toronto Collaborative Project Agreement (Stott and Halls, this volume); and 5) a compilation of the geology of the Mid-Continent Rift conducted in collaboration with the United States Geological Survey (USGS), the Minnesota Geological Survey and the Wisconsin Geological and Natural History Survey. A compilation of unpublished lithogeochemical data of Osler Group volcanic rocks continued in 2002 and included a reanalysis of more than 400 rock sample pulps in OGS archives collected during previous OGS mapping projects conducted in the Lake Nipigon region. The samples were collected from a variety of mafic to ultramafic intrusive rocks and metavolcanic rocks and are being analyzed for platinum group elements.

PGS staff are also currently participating on the Implementation and Science committees of the Lake Nipigon Region Geoscience Initiative, which is operated by the Ontario Prospectors Association and supported by a conditional award from the Northern Ontario Heritage Fund. The goal of the initiative is to generate new geoscience data and ideas for the Lake Nipigon area in order to understand the geological and metallogenic evolution of the region and to stimulate mineral exploration for a variety of mineral deposit types, including magmatic nickel-copper-platinum group element mineralization and Olympic Dam-type iron-copper-uranium-gold mineralization.

Initiatives Involving Geophysical Projects

The following geophysical projects and activities were conducted under the geophysics and rock properties data set initiative and are described in more detail in Rainsford and Muir (this volume):

1. An aeromagnetic levelling project was conducted to enhance the quality of aeromagnetic datasets held by the Ontario Geological Survey (OGS). A total of 35 surveys were reprocessed, as part of the Operation Treasure Hunt initiative, to reduce them to a common geomagnetic datum, a total of 35 surveys were reprocessed.
2. An airborne geophysical data reformatting project was completed in response to suggestions from clients. Thirty-three airborne geophysical survey data sets are being converted from older and proprietary database formats to more commonly used Geosoft® and universally accessible ASCII formats as part of the Operation Treasure Hunt initiative.
3. A collaborative physical rock properties study was completed under the Operation Treasure Hunt initiative. Methods and preliminary results are discussed in Deschamps (2000, 2001) and Deschamps and Morris (2001). PGS is integrating magnetic susceptibility data collected by bedrock mapping field crews into the rock properties database and are assessing the feasibility of conducting ongoing rock properties data collection as part of each bedrock mapping project. These data will be incorporated into a database and will result in more effective interpretation and modelling of the results of airborne geophysical surveys through the use of comparative ground-controlled measurements.
4. A 11 133 line kilometre MEGATEM II® survey was flown, by Fugro Airborne Surveys Inc., north of Timmins in February and March of 2002. The greater depth of penetration of this survey will provide explorationists with a superior tool to explore an area, which has the potential to host economic base and precious metal deposits and is overlain by thick, conductive overburden. The survey was jointly funded by FedNor (Industry Canada), Falconbridge Limited, the OGS, and the GSC, which also supervised the project as part of the Discover Abitibi! initiative.

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3. Project Unit 00-029. Measuring the Results of Ontario Geological Survey Projects: Impact of Operation Treasure Hunt

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INTRODUCTION

Over the past several years, the Ontario Geological Survey (OGS) has documented the impact of its geological survey projects. Aspects of the OGS documentation and analysis are derived from the practices and theories of results-based management (RBM) used by many organizations and supplemented by OGS practices. The OGS is conservative in its approach using only those figures that can be justifiably supported.

Government accountability requires that government programs

- demonstrate value for public investment;
- link project costs to results;
- effectively manage project-related information to ensure optimal program delivery to meet Government and client needs and objectives.

The goal of the long-term impact analysis of the OGS geoscience projects is to demonstrate and quantify the degree to which the design and delivery of OGS geoscience projects are effective in meeting government and clients needs and priorities (Churchill 1998; Churchill and Fyon 1999; Churchill et al. 2000, 2001), which include

- accountability for public funds;
- retaining and attracting mineral investment to Ontario;
- stimulating mineral or other resource exploration, advanced exploration and mine development;
- influencing private sector minerals investment decisions in Ontario;
- contributing to science and technology capacity of Ontario-based industry;
- contributing to informed land-use decisions.

In this article, a preliminary assessment of the impact of the Operation Treasure Hunt (OTH) geoscience program, a $29-million, three-year geoscience survey program is presented.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.3-1 to 3-5.

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CONTEXT FOR OPERATION TREASURE HUNT ASSESSMENT

In spring 2002, the Ontario Ministry of Northern Development and Mines (MNDM) commissioned an independent assessment of the impact of the OTH geoscience program. A questionnaire was designed to assess

- client awareness of the OTH geoscience program;
- the extent to which clients obtained products offered through OTH;
- the extent to which clients made use of the OTH products;
- customer satisfaction with the OTH products;
- how the OTH products affected investment in mining activities;
- impact of OTH on jobs in the mineral exploration sector.

Indications from staking levels and anecdotal evidence suggest a correlation between the release of OTH survey results, other geoscience products, and an increase in mineral exploration activity (Churchill et al. 2001). The results of the client survey, in conjunction with tracking of claim staking patterns, will provide insight into the economic impact of OTH and will test how the OTH products advanced key government priorities in job creation, economic development and the nurturing of a culture of innovation.

Survey Methodology

In March 2002, approximately 180 clients were randomly selected from a client list provided by MNDM. The consultant asked a standard set of questions. The clients surveyed included prospectors, exploration geologists, exploration managers and consultants. Most of those surveyed were based in Ontario. The survey questionnaire, which took about 20 minutes to administer, was designed by the consultant in consultation with the OGS.

Preliminary Analysis

Awareness of Operation Treasure Hunt is high, with nearly 8 in 10 respondents (79%) reporting to have seen, read or heard of the OTH geoscience program (Table 3.1).

Client satisfaction with OTH is very favourable. Of the 92% of respondents who rated their satisfaction level with the Operation Treasure Hunt program, 87% reported that they were satisfied or very satisfied (*see* Table 3.1). This satisfaction is based primarily on 3 key functions of the OTH program:

- it has provided new data (24%);
- stimulated mineral exploration (22%);
- provided useful geoscience data (20%).

Most respondents (94%) agreed that the OTH program provided relevant data and that it generated new exploration targets (87%). Approximately 8 in 10 respondents agreed that Operation Treasure Hunt caused increased investment in prospecting and exploration in Ontario (81%), and that the program introduced new ways for the prospecting and exploration community to access and obtain geological information (79%).

Table 3.1. Synthesis of results from the Operation Treasure Hunt (OTH) client satisfaction survey.

OTH GOALS AND OBJECTIVES	
Did OTH meet it goals and objectives? Stated goal: Attract and maintain mineral investment to Ontario by providing new geoscience data and defining exploration targets to stimulate mineral exploration.	The respondents identified the following top 5 reasons why they were satisfied with the OTH program, relevant to OTH goals and objectives. As a geoscience program, OTH • provided new and useful geoscience data • stimulated exploration • reduced exploration risk • demonstrated Government support for the mineral exploration (sector) Specifically • 87% of respondents stated that "OTH generated new exploration targets"; • 94% stated that "OTH provided relevant data"; • 81% stated that "OTH increased investment in Ontario". • 79% stated "OTH introduced new ways for the prospecting and exploration community to access and obtain geological information".
MARKETING EFFECTIVENESS	
Market Effectiveness Did MNDM efforts to inform and raise client awareness about OTH actually "reach" clients?	79% of respondents were aware of OTH as a result of • MNDM Mines and Minerals Division staff communication • conferences • OTH website • word-of-mouth • industry publications and newspapers
Market Penetration Did clients actually buy the OTH products?	Over 70% of respondents purchased or are likely to purchase OTH products.
Market Penetration Did clients actually use the OTH products they bought?	Over 70% of product owners used all published OTH products.
CLIENT SATISFACTION	
Client Satisfaction: OTH Program Are clients satisfied with Operation Treasure Hunt program?	Of the 92% of respondents who rated their satisfaction level with the Operation Treasure Hunt program, 87% reported that they were satisfied or very satisfied.
Client Satisfaction: OTH Products Are clients satisfied with Operation Treasure Hunt products?	Over 80% of respondents were satisfied with the OTH products.
INVESTMENT	
Investment: General Climate Past investment: did you invest more, less, or about the same in Ontario?	• 39% more • 37% about the same
Past investment increase in Ontario attributed to OTH.	46% of those who increased investment attributed that decision, in whole or part, to OTH.
Future investment in Ontario.	88% currently plan on investing the same, or more, in Ontario in the future.
Future investment increase in Ontario attributed to OTH.	46% of those who plan to increase investment in Ontario attribute that decision, in whole or part, to OTH.
Investment: Jobs Has the number of jobs stayed the same or increased over the last 3 years (not specifically attributed to OTH)?	69% of respondents stated that the number of jobs increased or remained the same over the last 3 years.

The respondents who purchased OTH products do use the products. The overall client satisfaction levels for each product is very high – the lowest satisfaction level is 80%. Three main reasons stand out to account for the client satisfaction: most of the products provided useful and accurate information; the products identified new exploration targets; and the products meet client needs.

Insight into investment and job creation must be viewed cautiously given that

1. the questionnaire survey was conducted prior to completion of the OTH geoscience program;
2. the OTH products will influence and be used by clients for the next 20 to 50 years; and,
3. access to investment capital is extremely difficult in the present global financial market.

Of the 21% who reported that the number of jobs in their company has increased over the past 3 years,

- 51% said that at least one job had been added as a direct result of OTH;
- One in 10 said one job had been added as a direct result of OTH;
- One in 10 reported an increase of 5 jobs because of OTH; and,
- a further 1 in 10 said between 10 and 20 jobs had been added as a direct result of OTH.

Approximately 42% of respondents stated that they currently plan on increasing their investment in Ontario through prospecting, exploring or mining in the near future. Of these respondents, 24% have stated that they will spend between $100 000 and $500 000 on these activities. Fifty percent of the survey respondents acknowledged that Operation Treasure Hunt was one of the reasons behind planned future investment increases.

SHORT-TERM IMPACT: LAKE NIPIGON REGION CASE EXAMPLE

The cause-and-effect relationship between the OGS geoscience products and services, including OTH products, and attributed industry mineral exploration investment is illustrated by a case example selected from the west side of Lake Nipigon (Figure 3.1).

Since February 1998, one year before the announcement of the OTH geoscience program, the number of total claims in good standing in the case study area increased from about 10 000 to about 60 000 following the release of the geoscience survey results and recommendations (*see* Figure 3.1). The short-term impact attributed to the OGS surveys and services is a six-fold increase in the number of active claims and an industry investment of about $3 million for each $1 million in public investment, despite the very short time following the release of the survey data.

CONCLUSIONS

The survey results indicate that OTH is having an overall positive impact upon the mineral industry.

- OTH provided useful geological data and did reveal new exploration targets.
- OTH products did meet client needs.
- The OTH geoscience data will continue to provide value and a return on the public investment for many years to come.
- Despite the delivery of the OTH geoscience program during one of the worst global economic downturns on record, OTH did stimulate investment in the Ontario minerals industry.

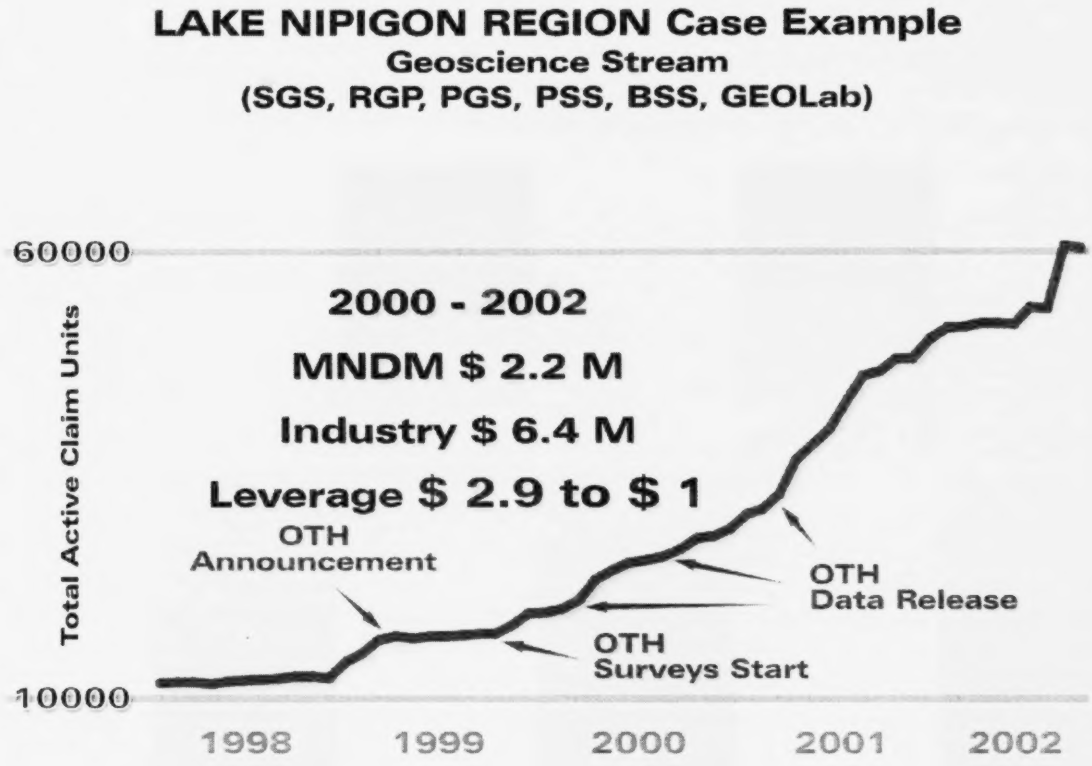

Figure 3.1. Change in total active mining claims, measured for the area along the west side of Lake Nipigon. An Operation Treasure Hunt airborne geophysical survey, a lake sediment survey, and several bedrock mapping projects were conducted over this area. OGS Resident Geologist staff actively promoted the area. The approximate dates of key milestones and data releases are indicated. Total active claims are those claims in active standing on the date of this report. Abbreviations: OTH, Operation Treasure Hunt geoscience program; M, million; SGS, Sedimentary Geoscience Section; RGP, Resident Geologist Program; PGS, Precambrian Geoscience Section; PSS, Publications Services Section; BSS, Business Solutions Section; GEOLab, Geoscience Laboratories

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4. The Abitibi Greenstone Belt: A Program Update

J.A. Ayer

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INTRODUCTION

The Precambrian Geoscience Section program in the Abitibi greenstone belt (AGB) is designed to facilitate exploration by providing current geological mapping in areas of high mineral potential at a variety of map scales. We are also actively involved in research on the metallogenic and tectonic evolution of the belt and applied research on specific mineral deposit-related problems through jointly funded partnership projects with mining companies, the geology departments of several universities (i.e., University of Ottawa, Laurentian University) and other government agencies (i.e., Geological Survey of Canada). Parker (this volume) lists current core projects and collaborative partnership agreements.

CURRENT PROJECTS

To date, the Abitibi compilation project has produced hard copy and digital versions of the Timmins, Lake Abitibi, Kirkland Lake and Swayze map areas at a scale of 1:100 000 (Ayer and Trowell 1998; Ayer, Trowell and Berger 1999; Ayer and Trowell 2000; Ayer and Trowell 2002). A compilation sheet covering the Matachewan area (A on Figure 4.1) is planned for release in 2003. The compilation, in conjunction with new geochronological and lithogeochemical sampling, will enable further review and refinement of the assemblages (Ayer et al. 2002; Ayer, Ketchum and Trowell, this volume); help to establish a more formalized stratigraphy; and help to construct new metallogenic and geodynamic models for the evolution of the Abitibi greenstone belt. In addition, a number of ongoing mapping and research projects at a variety of scales (discussed below) are designed to focus on areas where we currently have an inadequate understanding of the relationships between mineralization and geology, and to provide new data for the ongoing compilation project.

The author is the Ontario Geological Survey's representative on the Technical Committee of the Discover Abitibi! initiative, This is a community based and directed program designed to stimulate exploration for, and eventual development of, mineral deposits within the Abitibi greenstone belt of northeastern Ontario. The program will be achieved through the co-operation and collaboration between Federal, Provincial and Municipal governments and private-sector partners. Products currently developed under the Discover Abitibi! initiative include

1. a digital compilation of data (Panagapko et al. 2002), jointly produced by the Geological Survey of Canada and the Ontario Geological Survey, containing a wide range of geoscience information collected over the Abitibi greenstone belt (B on Figure 4.1) in northeastern Ontario using geographic information system (GIS) technology;
2. a 11 133 line km MEGATEM® II survey, flown north of Timmins (C on Figure 4.1) to be released in the latter part of this year (Rainsford and Muir, this volume). It is anticipated that the greater depth of penetration of the EM system will provide explorationists with a superior tool to explore an area that has the potential to host economic base and precious metal deposits and is overlain by thick, conductive overburden. The survey was jointly funded by FedNor (Industry Canada), Falconbridge Limited, the Ontario Geological Survey, and the Geological Survey of Canada, who also supervised the project as part of the Discover Abitibi! initiative.

Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.4-1 to 4-5.

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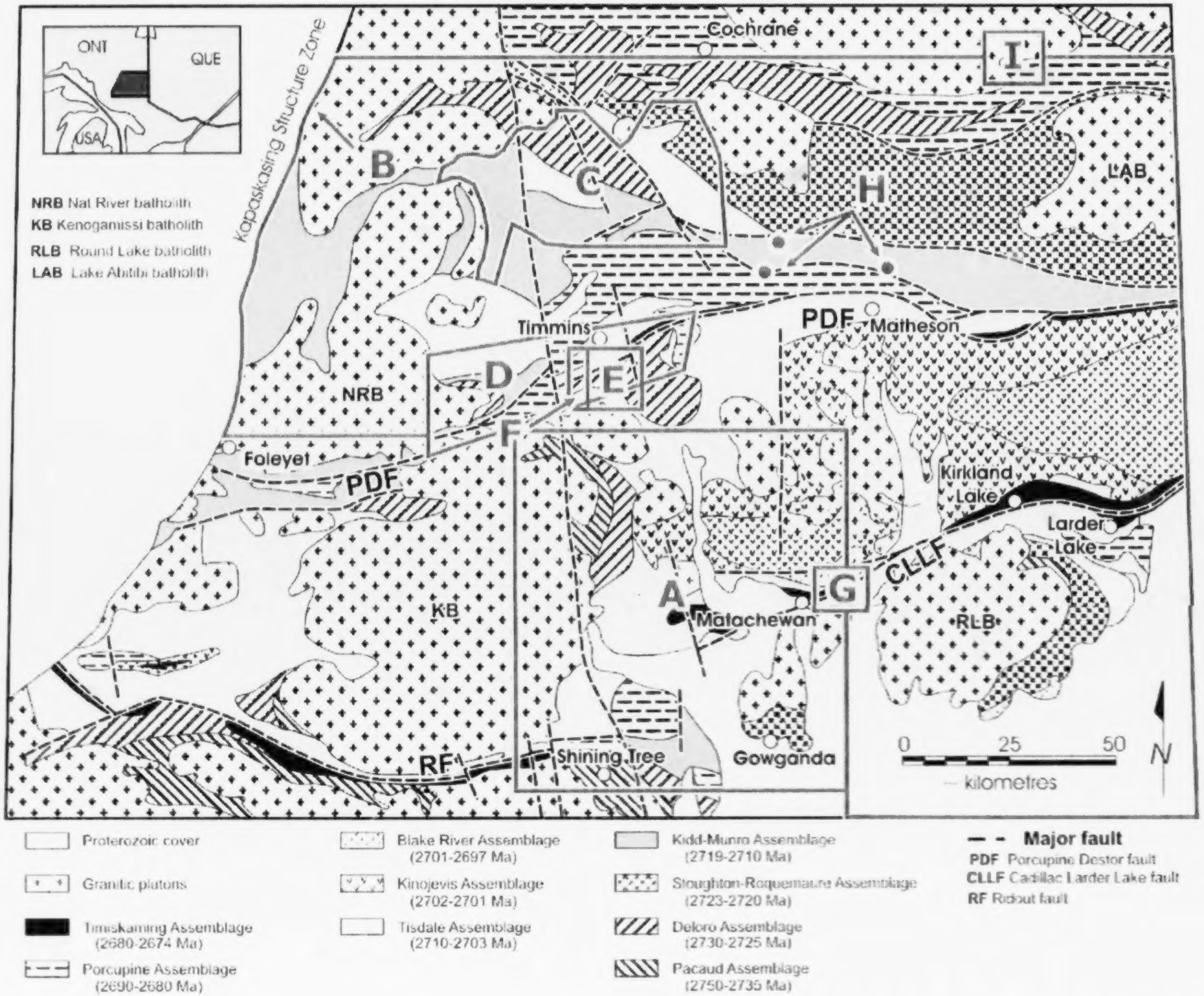
ONT
QUE
USA
NRB Nat River batholith
KB Kenogamissi batholith
RLB Round Lake batholith
LAB Lake Abitibi batholith
Kapuskasing Structure Zone
Cochrane
I
B
C
H
LAB
Timmins
PDF
Matheson
D
E
F
NRB
Foleyet
PDF
Kirkland Lake
Larder Lake
CLLF
A
Matachewan
G
KB
RLB
RF
Shining Tree
Gowganda
0 25 50
kilometres
N
Proterozoic cover
Granitic plutons
Timiskaming Assemblage (2680-2674 Ma)
Porcupine Assemblage (2690-2680 Ma)
Blake River Assemblage (2701-2697 Ma)
Kinojevis Assemblage (2702-2701 Ma)
Tisdale Assemblage (2710-2703 Ma)
Kidd-Munro Assemblage (2719-2710 Ma)
Stoughton-Roquemaure Assemblage (2723-2720 Ma)
Deloro Assemblage (2730-2725 Ma)
Pacaud Assemblage (2750-2735 Ma)
Major fault
PDF Porcupine Destor fault
CLLF Cadillac Larder Lake fault
RF Ridout fault

Figure 4.1. Location map of the Abitibi greenstone belt for projects mentioned in the text of this article. Letters on the figure correspond to letters in the text.

An Open File Report and 1:50 000 metamorphic map by P. Thompson, covering portions of 8 townships from Keefer to Whitney (D on Figure 4.1), will be released in December of this year. This project was done in collaboration between Placer Dome CLA Limited and the Precambrian Geoscience Section. This work indicates there may be a correlation between the biotite isograd and a number of the Timmins Camp gold deposits. This suggests that mineralized areas are underlain by rocks which have experienced higher temperatures than the surrounding rocks and, thus, the presence of metamorphic biotite may be useful as a new exploration tool.

This year's mapping of Deloro Township (E on Figure 4.1) at 1:20 000 scale by L.A.F. Hall continues a multiple year project (Vaillancourt 2000; Hall 2001) to improve our knowledge of the distribution of rock units, structures and mineralization in poorly understood parts of the Timmins area. Deloro Township, in proximity to the Porcupine–Destor fault (PDF), has good potential for the discovery of new gold deposits and nickel-copper deposits in the komatiitic units. Additional field work is also being undertaken by C. Vaillancourt in Ogden Township (F on Figure 4.1) in conjunction with the mapping of Deloro Township by L.A.F. Hall to better understand the lithological and structural relationships along the township boundary.

Cairo Township (G on Figure 4.1) was mapped at 1:20 000 scale this summer (Berger and Leblanc, this volume) in a multiple year project to map a number of townships along the Cadillac – Larder Lake fault (CLLF) between Matachewan and Kirkland Lake. The mapping highlights a number of mineralization environments including auriferous zones associated with the CLLF and its splay structures; barite veins associated with the Cairo stock; and base metal potential (magmatic nickel-copper mineralization and volcanogenic copper-zinc mineralization) associated with the metavolcanic rocks.

Collaborative projects with the Mineral Exploration Research Centre (MERC) at Laurentian University have the goals of examining the spatial and stratigraphic variations in AGB komatiites in order to provide constraints on their petrogenesis and the stratigraphic architecture and assembly of the Abitibi greenstone belt (Sproule et al. 2002; Houlé et al. 2001). An ongoing PhD thesis project has the aim of studying the volcanic facies of komatiites in the AGB in order to constrain stratigraphic, tectonic and metallogenic models and to help constrain the volcanic architecture of komatiite flow fields. In this year's report, Houlé et al. (this volume) provide detailed observations on the geological controls on magmatic nickel-copper – platinum group elements (PGE) mineralization in Dundonald Township, and volcanogenic copper-zinc mineralization associated with komatiitic and mafic metavolcanic rocks at the Potter Mine in Munro Township (H on Figure 4.1). This new information will aid in future exploration for volcanic-hosted base metal deposits in the Abitibi greenstone belt.

A PhD thesis project, by H.S. Oliver at University of Portsmouth, UK, has documented the geochemical patterns of the various Archean rock packages in the Shining Tree area (Oliver et al. 2000). These data will be used in conjunction with the mapping by G.W. Johns, who is currently completing a synoptic Open File Report and 1:50 000 scale map of the Shining Tree area (not depicted on Figure 4.1).

In addition to exploration for diamonds in the traditional setting of Jurassic-age kimberlite, the Michipicoten greenstone belt at Wawa and the Abitibi greenstone belt in the Cobalt area have been the focus of recent exploration for diamonds in Archean-age lamprophyre dikes and associated heterolithic breccias. Stott et al. (this volume) point out some of the features of these rocks and speculate that they may be related to a craton-wide, late-tectonic, alkalic magmatic event that tapped Archean upper mantle sources within the diamond stability field. Thus, late-tectonic rocks of alkalic affinity and, in particular, the associated breccias, which may represent relatively larger volume targets than the lamprophyre dikes, represent a newly discovered source of diamonds that should be explored throughout the Superior Province.

Recent work by Breaks, Selway and Tindle (this volume) has focussed on the rare-element potential of the pegmatite system in the southeastern part of the Case batholith, northeast of Lake Abitibi (I on Figure 4.1). The newly documented pattern of beryl to spodumene fractionation, coupled with the potassium feldspar mineral chemistry within the pegmatite dike swarm indicates that even more fractionated dikes, enriched in cesium and tantalum mineralizaton, could lie within this area of poor exposure.

CONCLUSIONS

In summary, many exciting new advances in our understanding of the geology of the Abitibi greenstone belt are being made. The following reports in this volume demonstrate the merits of a diverse, but balanced, approach to Abitibi area geology using the traditional strengths of Precambrian Geoscience Section bedrock mapping, the comprehensive understanding of the ore deposits by the mining companies working in the area and the research skills of university geology departments. This balanced approach embraces projects at a wide variety of scales and methodologies that are required for the range of problems that exist. The projects range from belt-wide compilation, to township-scale bedrock mapping to extremely detailed outcrop-scale mapping. The program is also focussed on the economically important parts of the belt. We feel our integrated approach to applied research through collaboration with our mining company clients and the earth science departments of a number of universities is needed to advance our understanding of the geology and its relationship to mineral deposits in this geologically complex, but highly productive, part of the province. We also feel confident that the maps, reports and theses resulting from this comprehensive program will provide many new ideas and concepts that are, and that will continue to be, directly applicable to exploration for new mineral deposits.

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5. Project Unit 95-024. New Geochronological and Neodymium Isotopic Results from the Abitibi Greenstone Belt, with Emphasis on the Timing and the Tectonic Implications of Neoarchean Sedimentation and Volcanism

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INTRODUCTION

Ongoing tectonostratigraphic revision in the southern Abitibi greenstone belt (SAGB) has utilized U/Pb geochronological data and the results of a regional-scale geological compilation in the subdivision of supracrustal rocks into 9 stratigraphic assemblages (Table 5.1) (Ayer et al. 2002). This work is focussed on improving our understanding of the stratigraphy and absolute timing of the volcanic assemblages in the Gowganda and Halliday areas and the late-tectonic sedimentary and volcanic assemblages in the Timmins, Larder Lake, Matachewan and Swayze areas. New U/Pb zircon geochronological results presented herein provide data for some changes to the tectonostratigraphic model (Figure 5.1). Specifically, our data refine the timing of deposition of the late-tectonic Porcupine and Timiskaming assemblages and the deformation episodes that resulted in regional-scale folding and faulting.

All rock types described in this report have been metamorphosed. Thus, the prefix "meta" has been omitted for the sake of brevity.

U/Pb analyses were conducted at the Jack Satterly Laboratory, Royal Ontario Museum and involved standard rock crushing, mineral separation, zircon selection, zircon dissolution, and thermal ionization mass spectrometry techniques. Zircons were air abraded to reduce discordance and were analyzed without chemical isolation of uranium and lead due to their small size (almost all <3 μg). The vast majority of analyses represent single zircon crystals. Age uncertainties cited in the text and shown in concordia plots are given at the 95% confidence level.

Determination of neodymium isotopic data was supported by the Operation Treasure Hunt initiative and analyses were conducted at Carleton University, Ottawa, Ontario. Whole rock powder was dissolved and analysed utilizing techniques described in Cousens (1996). Total procedural blanks for Nd are less than 75 pg. The internal 2 sigma (2σ) uncertainties of the means of Nd analyses were typically 0.002%, and external reproducibilities based on replicate runs were 0.004%.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.5-1 to 5-16.

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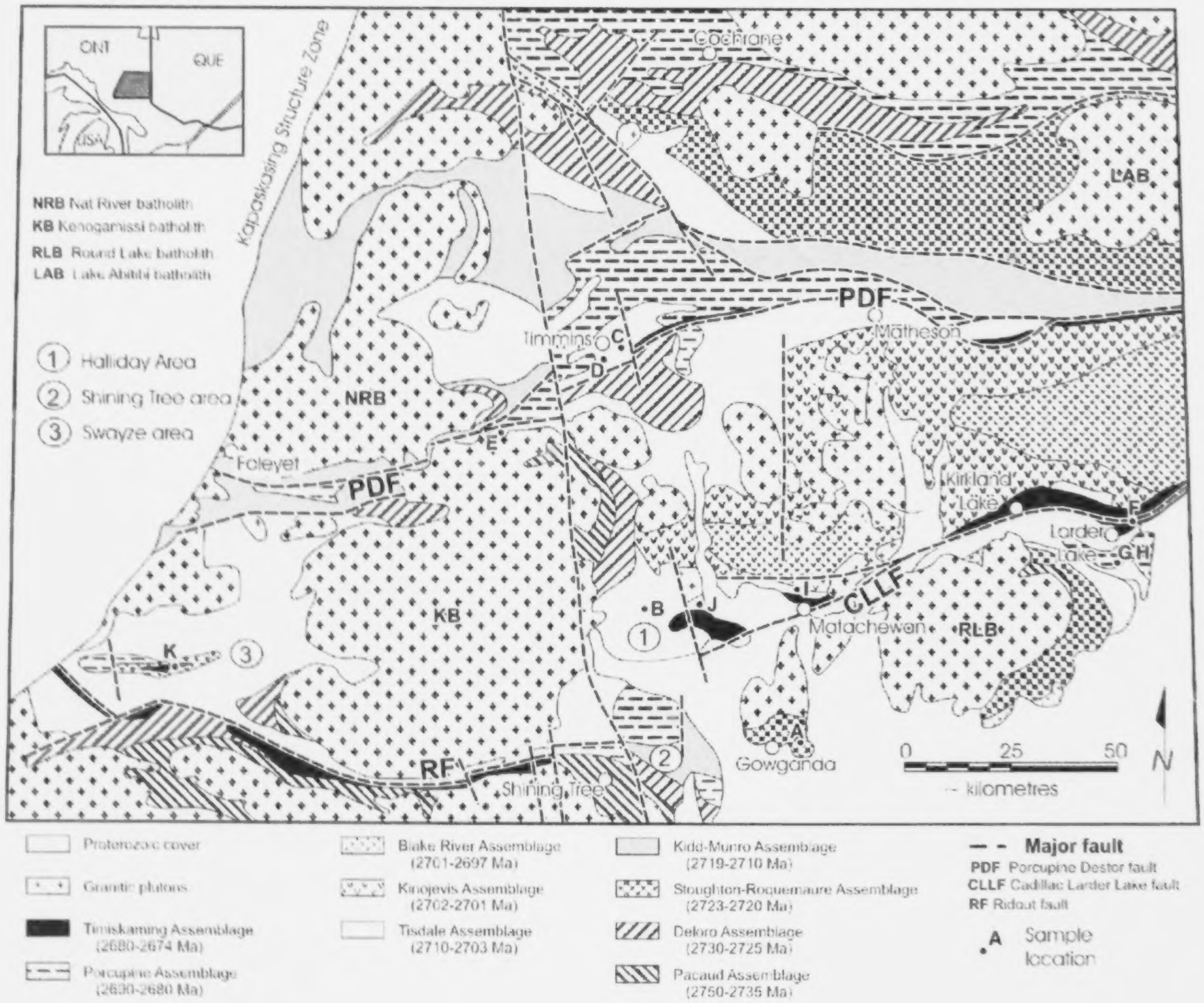
ONT
QUE
USA
Kapuskasing Structure Zone
NRB Nat River batholith
KB Kenogamissi batholith
RLB Round Lake batholith
LAB Lake Abitibi batholith
① Halliday Area
② Shining Tree area
③ Swayze area
Cochrane
LAB
PDF
Matheson
Timmins
C
D
NRB
E
Foleyet
PDF
Kirkland Lake
F
Larder Lake
G H
KB
B
J
I
CLLF
Matachewan
RLB
K
A
Gowganda
RF
Shining Tree
0 25 50
kilometres
N
Proterozoic cover
Granitic plutons
Timiskaming Assemblage (2680-2674 Ma)
Porcupine Assemblage (2690-2680 Ma)
Blake River Assemblage (2701-2697 Ma)
Kinojevis Assemblage (2702-2701 Ma)
Tisdale Assemblage (2710-2703 Ma)
Kidd-Munro Assemblage (2719-2710 Ma)
Stoughton-Roquemaure Assemblage (2723-2720 Ma)
Deloro Assemblage (2730-2725 Ma)
Pacaud Assemblage (2750-2735 Ma)
Major fault
PDF Porcupine Destor fault
CLLF Cadillac Larder Lake fault
RF Ridout fault
A Sample location

Figure 5.1. Distribution of southern Abitibi greenstone belt assemblages in Ontario (*see* Table 5.1 for details). Letters indicate the locations of samples used for U/Pb geochronology discussed in the text.

Table 5.1. Summary of southern Abitibi greenstone belt supracrustal assemblage names, ages, basal contacts, rock types and chemical affinities.

Assemblage Name (Age in Ma)	Basal Contact Relationships	Dominant Rock Types	Volcanic Chemical Affinity
Timiskaming (2680–2674)	Unconformable	Conglomerate, sandstone, mafic to intermediate volcanic and iron formation	Alkalic to shoshonitic
Porcupine (2690–2680)	Unconformable	Turbidite, felsic to intermediate volcanic, conglomerate and iron formation	Calc-alkalic to shoshonitic
Blake River (2701–2697)	Conformable to disconformable	Mafic to felsic volcanic	Tholeiitic and calc-alkalic
Kinojevis (2702–2701)	Conformable	Mafic and minor felsic volcanic	Tholeiitic
Tisdale (2710–2703)	Conformable to disconformable	Ultramafic, mafic, intermediate to felsic volcanic and iron formation	Komatiitic, tholeiitic and calc-alkalic
Kidd–Munro (2719–2711)	Conformable to disconformable	Ultramafic, mafic, intermediate and felsic volcanic and iron formation	Komatiitic, tholeiitic and calc-alkalic
Stoughton–Roquemaure (2723–2720)	Conformable to disconformable	Ultramafic, mafic, intermediate and felsic volcanic	Komatiitc, tholeiitic and calc-alkalic
Deloro (2730–2724)	Disconformable	Mafic, intermediate and felsic volcanic and iron formation	Tholeiitic and calc-alkalic
Pacaud (2750–2735)	Unknown (removed by intrusions)	Ultramafic, mafic and felsic volcanic	Komatiitic, tholeiitic and calc-alkalic

GEOCHRONOLOGICAL RESULTS OF KEEWATIN ASSEMBLAGE SAMPLES

Gowganda Area

No U/Pb zircon age determinations have been carried out in the Gowganda area prior to the compilation project. Here, an Archean inlier, surrounded by Proterozoic cover rocks (*see* Figure 5.1), consists dominantly of mafic volcanic rocks intruded by granitic rocks of the Round Lake batholith. Ayer et al. (2002) previously speculated that the supracrustal rocks in this belt were correlative with the Kidd–Munro assemblage situated immediately to the west in the Shining Tree area.

Archean supracrustal rocks with adequate material for precise geochronology are rare in this area, but zircons were found in a thinly layered feldspathic siltstone-sandstone intercalated with basalts along Highway 560, about 5 km east of Gowganda in Nicol Township (*see* Figure 5.1, sample A). The epiclastic unit is interlayered with strongly foliated quartz-feldspar porphyritic tuffs or sills.

A small yield of colourless to light pink, equant to 2:1 (length:breadth) zircon grains were extracted from the sample. Some grains may have metamorphic overgrowths, but this could not be determined with certainty. Detrital pitting is rare and most grains preserve crystal faces or are smoothly rounded. The morphological similarity of all zircons suggests the likelihood of a single source. Four strongly abraded single grains provide a tight range of concordant ages (Figure 5.2a). The weighted mean ^{207}Pb/^{206}Pb age of 3 grains is 2719.1±1.1 Ma (95% probability of fit) and this represents the maximum depositional age (and may be close to the true depositional age). A fourth grain is slightly older at

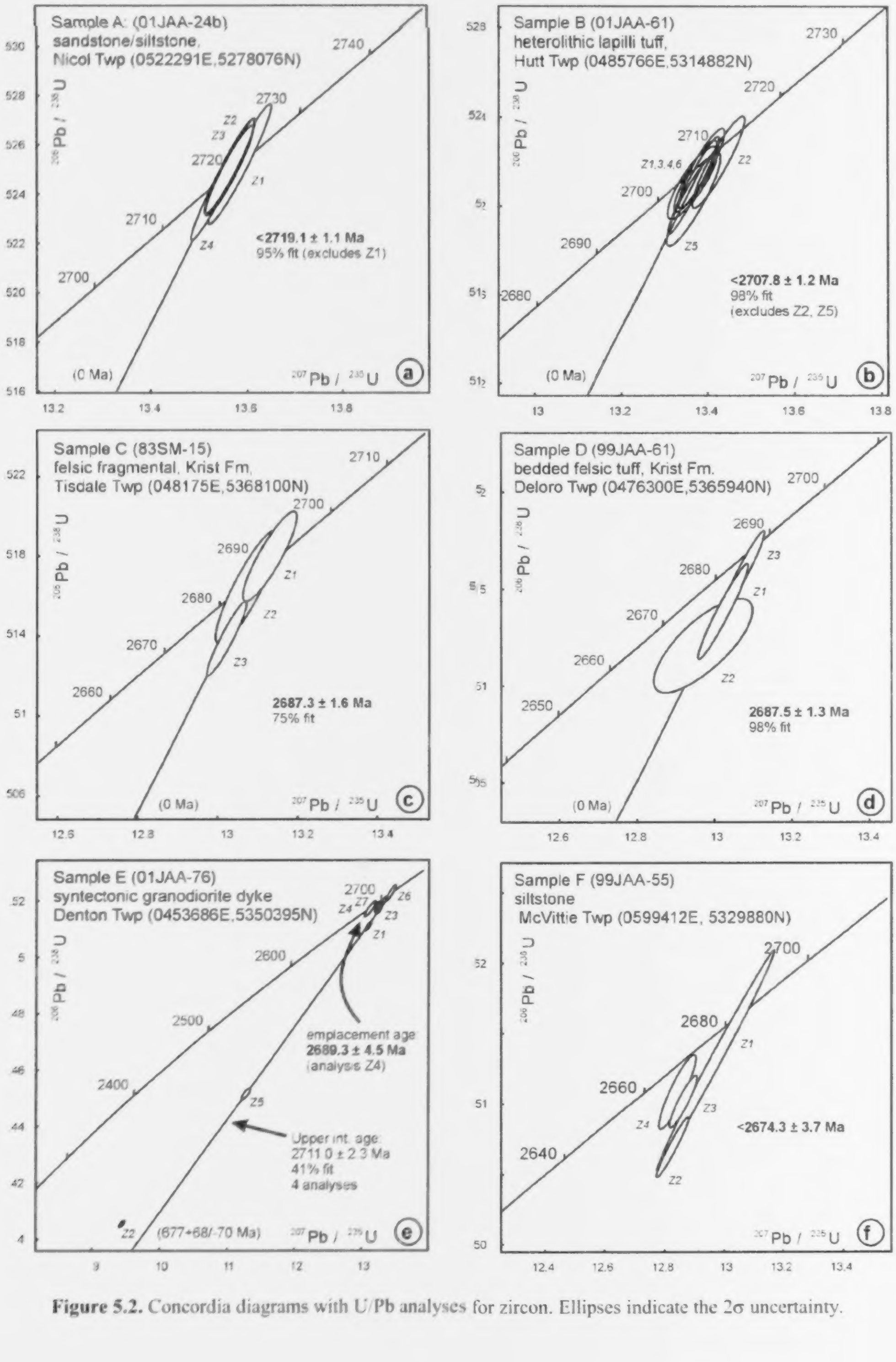

Figure 5.2. Concordia diagrams with U/Pb analyses for zircon. Ellipses indicate the 2σ uncertainty.

2721.3±2.2 Ma. These data indicate that the predominantly mafic volcanic rocks in this area are similar in age to the Catherine Formation of the Stoughton–Roquemaure assemblage (Ayer et al. 2002). This suggests that the outward facing stratigraphy found on the east side of the Round Lake batholith (*see* Figure 5.1) also extends to the southwest.

Halliday Area

The Halliday area is underlain by extensive calc-alkalic intermediate to felsic volcanic rocks that were speculated to lie in the core of a domal structure flanked by ultramafic and mafic volcanic rocks to the north, west and south, and unconformably overlain by sedimentary rocks to the east (Bright 1970).

Our geochronological results help to constrain the structure and stratigraphy of this area. A rhyolite flow from the central part of this volcanic complex in Midlothian Township previously yielded an age of 2710.5±1.6 Ma (Ayer et al. 2002). We have now also sampled lapilli tuff, containing heterolithic, felsic to mafic volcanic clasts, that is part of a package of predominantly mafic and ultramafic volcanic rocks on the northern flank of the "Halliday Dome" in Hutt Township (*see* Figure 5.1, sample B). The zircon population is dominated by prismatic euhedral and subhedral brown grains lacking evidence of detrital pitting. Cores are visible in some grains and were avoided during selection of a representative population for air abrasion. Six concordant single grain analyses cluster tightly together, and of these, 4 closely overlap with an average ^{207}Pb/^{206}Pb age of 2707.8±1.2 Ma (Figure 5.2b). This age is a maximum for deposition of the lapilli tuff and is most likely the age for the unit and the associated komatiitic and mafic flows. The remaining fractions have slightly older ages of 2710.1±3.5 Ma and 2711.8±2.9 Ma. Although the data are limited, they suggest a slightly older detrital input into a volcaniclastic package dominated by zircons that are circa 2710 Ma.

The stratigraphic succession in the Halliday area is different from the succession commonly found between the Porcupine–Destor fault (PDF) and Cadillac–Larder Lake fault (CLLF), in which the upper part of the Deloro assemblage (2725 Ma) is typically disconformably overlain by komatiitic and mafic volcanic flows (circa 2707 Ma) of the Tisdale assemblage (Ayer et al. 2002). The above new age indicates that the extensive calc-alkalic volcanic complex centred in Halliday Township occupies the core of a regional, west-facing anticline containing the oldest part of the Tisdale assemblage (circa 2710 Ma) and is overlain by mafic and ultramafic volcanic rocks to the north, west and south. This suggests that the Halliday area may have originally been a localized topographic high underlain by a calc-alkalic stratovolcano, which developed from 2710 to 2708 Ma and was subsequently surrounded by the widespread basaltic and komatiitic flows more typically found at the base of the Tisdale assemblage.

GEOCHRONOLOGICAL RESULTS ON PORCUPINE AND TIMISKAMING ASSEMBLAGE SAMPLES

There has been a considerable amount of field work and some geochronology documenting the stratigraphy and variation in facies and lithotypes for the late-tectonic clastic units in a number of areas of the SAGB (e.g., Hyde 1980; Pyke 1982; Corfu, Jackson and Sutcliffe 1991; Mueller, Donaldson and Doucet 1994; Born 1995; Bleeker, Parrish and Sager-Kinsman 1999). Our geochronological data provide some additional insight on the age of these assemblages and the regional deformation events in the Timmins, Kirkland Lake, Matachewan and central Swayze areas.

Timmins Area

The Porcupine assemblage consists predominantly of wacke, siltstone and mudstone displaying Bouma sequence subdivisions indicating distal deposition by turbidity currents, but locally also contains minor conglomerate and iron formation. Born (1995) subdivided the sedimentary units in the Timmins area into an early, dominantly turbiditic facies Porcupine Group, unconformably overlain by an alluvial fan-fluvial facies Timiskaming Group.

PORCUPINE ASSEMBLAGE

Born (1995) classified the turbiditic sedimentary rocks of the Porcupine Group into 3 different formations: 1) the Whitney Formation lying south of the Porcupine–Destor fault (which he correlated with the Tisdale Group); 2) the Beatty Formation, which conformably overlies calc-alkalic volcanic rocks of the Krist Formation in Tisdale Township; and 3) the Hoyle Formation, an extensive unit lying north of Timmins. Geochronology from 2 samples collected from the Hoyle Formation (Bleeker, Parrish and Sager-Kinsman 1999) indicated maximum depositional ages of 2699 Ma and 2685±6 Ma.

The Krist Formation is a felsic fragmental unit disconformably underlain by graphitic argillite and mafic volcanic rocks of the Tisdale assemblage (circa 2707 Ma). Based on our new geochronological results (discussed below), we now interpret that the Krist Formation and all of the turbiditic formations described above are members of the Porcupine assemblage. The original U/Pb zircon age determination of the Krist Formation by Corfu et al. (1989) was conducted on a sample of felsic fragmental volcanic rock conformably underlying Beatty Formation turbidites (*see* Figure 5.1, sample C). Multigrain zircon fractions yielded a mean ^{207}Pb/^{206}Pb age of 2698±4 Ma. This age was previously considered to represent the maximum depositional age of the conformably overlying turbidites of the Porcupine Group (Ayer et al. 2002). However, this interpretation is now modified based on new single grain analyses of fractions from the original sample collected from the Krist Formation by Corfu et al. (1989; sample TK or 83SM-15). Zircons from this sample are morphologically uniform and consist of colourless to light brown, small euhedral prisms, many of which have visible cores and/or igneous growth zoning. Therefore, care was taken in selecting a few high-quality grains, lacking these features, for laboratory abrasion. Analysis of 3 such grains yielded concordant to slightly discordant data with a considerably younger average ^{207}Pb/^{206}Pb age of 2687.3±1.6 Ma (75% fit; Figure 5.2c), which we interpret as the primary age of the Krist Formation.

This younger age for the Krist Formation is corroborated by a second sample from a diamond-drill hole in the southern part of the Kayorum syncline (*see* Figure 5.1, sample D). The sample of thickly bedded dacitic to rhyodacitic tuff has a single population of light brown to colourless, 2:1, euhedral to subhedral prisms, some with tip overgrowths. Grains with the least evidence of overgrowths were selected for strong abrasion. Three single grains yield essentially identical ^{207}Pb/^{206}Pb ages with an average age of 2687.5±1.3 Ma (Figure 5.2d) (98% probability of fit).

These new data indicate that the Porcupine assemblage turbidites were deposited shortly after 2687 Ma and that the original age of 2698 Ma (Corfu et al. 1989) for the Krist Formation likely reflects the presence of an inherited zircon component. The revised younger age for the Porcupine assemblage has significant metallogenic implications because it indicates that the age of Krist Formation felsic volcanism is within error of the age of a number of felsic porphyries (ranging in age from 2691±3 Ma to 2688±2 Ma; Corfu et al. 1989) that are interpreted to be associated with an early gold mineralization event in the Timmins camp (Gray and Hutchinson 2001).

TIMISKAMING ASSEMBLAGE

The Timiskaming assemblage constitutes the youngest supracrustal assemblage in the SAGB. In the Timmins area, it is confined to a narrow east-trending unit of conglomerate and sandstone overlying the Tisdale and Porcupine assemblages. An angular unconformity occurs along the north contact of the Timiskaming assemblage and it is truncated by the PDF to the south. Born (1995) subdivided the Timiskaming assemblage in this area into the lowermost Dome Formation, consisting of alluvial sediments grading upwards into proximal and mid-fan turbidites, which are overlain by the Three Nations Formation grading upwards from alluvial to fluvial to shelf facies sandstones. Corfu, Jackson and Sutcliffe (1991) sampled a sandstone from the Three Nations Formation for which the youngest detrital zircon age of 2679±3 Ma provided a maximum depositional age.

TIMING OF DEFORMATION AND GOLD MINERALIZATION

Our new geochronological data also have implications for the timing of regional deformation and gold mineralization in the Timmins area. Corfu (1993) suggested that the Porcupine Group was folded before emplacement of the Timmins porphyries. However, our new data show that the porphyries were emplaced shortly before, or during deposition of, the basal part of the Porcupine assemblage and, thus, it is likely that both units underwent regional folding sometime after 2687 Ma. Brisbin and Pressacco (1999) indicate that at least 2 episodes of deformation occurred prior to deposition of the Timiskaming assemblage based on fabric evidence and the truncation of older assemblages and structures by an unconformity at the base of the Timiskaming assemblage. In addition, Gray and Hutchinson (2001) have shown that auriferous boulders occur within Timiskaming assemblage conglomerates, which are crosscut by gold-bearing quartz-carbonate veins at the Dome and Pamour mines. Thus, gold mineralization events both predate and postdate the deposition of the Timiskaming assemblage in Timmins.

A granodiorite dike, in Denton Township, was sampled for geochronological determination (*see* Figure 5.1, sample E) to provide constraints on the timing of displacement along the PDF. At this location, numerous parallel to subparallel, pink weathering, granodioritic dikes intrude mylonitized mafic volcanic rocks within the PDF. The dikes are interpreted to have been emplaced during a period of dextral transpressive movement associated with regional D_2 folding (Hall 2001). Seven single-grain analyses from the granodiorite dike are concordant to strongly discordant (Figure 5.2e). Four analyses, including 1 concordant grain, define a lead-loss line with an upper intercept age of 2711.0±2.3 Ma; a second concordant analysis yields an age of 2701.4±2.8 Ma; a third concordant analysis gives an age of 2689.3±4.5 Ma. The 2 older ages probably reflect inheritance in the granodiorite dike, while the younger age most likely reflects the emplacement age. This age is within error of the age of the porphyry intrusions and the Krist Formation in the Timmins area (Corfu, Jackson and Sutcliffe 1991; this report) and suggests that early deformation on the PDF may be related to the development of the Porcupine assemblage basin.

The deformational history along the PDF is complex since deformation also continued after deposition of both the Porcupine and Timiskaming assemblages (Benn et al. 2001). This is further indicated by U/Pb geochronological data from the Holloway Mine, within the PDF, east of Timmins (Ropchan et al. 2002). Here, early gold mineralization associated with albitization and disseminated pyrite is constrained between 2687±2 Ma, the age of a heterolithic tuff breccia unit, and 2672±2 Ma, the age of a barren lamprophyre dike cutting the gold mineralization. The dike contains 2 fabric generations indicating that it was followed by ductile deformation, which was coeval with a second, quartz carbonate vein-hosted, gold mineralization event.

Larder Lake Area

The depositional ages of the late-tectonic sedimentary and volcanic successions in the Kirkland Lake – Larder Lake area are also enigmatic. Hyde (1980) subdivided sedimentary components of the Timiskaming Group into an early nonmarine association dominated by conglomerates and sandstone of braided river origin; and a later resedimented association consisting of turbidites, turbiditic conglomerates and oxide-iron formation representing submarine fan deposits. However, the timing of the resedimented association is controversial as Jensen and Langford (1985), Corfu, Jackson and Sutcliffe (1991) and Mueller, Donaldson and Doucet (1994) all interpreted the turbidite sequences as part of an older sedimentary association structurally overlying the Timiskaming assemblage. This is a stratigraphic and/or facies relationship analogous to the Porcupine and Timiskaming assemblages in the Timmins area.

Corfu, Jackson and Sutcliffe (1991) sampled a number of the nonmarine association facies sedimentary rocks in the Kirkland Lake and Larder Lake areas and determined their maximum age of deposition to be circa 2679 Ma. However, Corfu, Jackson and Sutcliffe (1991) did not sample the resedimented association facies. Therefore, the authors sampled 3 different turbiditic facies rocks from the "Hearst assemblage", which Jackson, Fyon and Corfu (1994) defined as the turbiditic sedimentary assemblage preceeding deposition of the Timiskaming assemblage. Detrital zircon populations from these samples have been evaluated to provide estimates for their maximum depositional age.

East of the town of Larder Lake, turbidites with thin oxide-iron formation interbeds were included in resedimented association and were interpreted by Hyde (1980) to overlie the nonmarine association sedimentary and volcanic rocks lying north of the CLLF. An outcrop south of the CLLF, on Highway 66 (*see* Figure 5.1, sample F), consists of foliated and folded greywacke interbedded with heterolithic conglomerate beds and minor-oxide iron formation. Only a few, very small, rounded, equant to 2:1 zircons lacking crystal faces were recovered from fine-grained sandstone sampled from this location. The zircon grains are light brown or colourless and of variable quality. A few exhibit core-overgrowth relationships and were not selected for abrasion. The 4 largest zircons after abrasion were analyzed. Three analyses are near-concordant with ^{207}Pb/^{206}Pb ages between 2684.9±1.9 Ma and 2674.3±3.7 Ma (Figure 5.2f). The remaining analysis overlaps concordia with an age of 2683.5±2.6 Ma. The data suggest that the unit was deposited sometime after 2674 Ma.

A sample collected from poorly sorted heterolithic conglomerate associated with turbidites on the west side of Highway 624, in Skead Township (*see* Figure 5.1, sample G), contains numerous small, subrounded to subangular, fine-grained, lithic fragments of ultramafic, mafic, and felsic composition in a sandy matrix. The detrital zircon population consists of a variety of good quality grains and grain fragments. Most are colourless, euhedral, equant to 2:1 prisms that lack evidence of extensive detrital transport (e.g., pitted grain surfaces). Lesser brown zircon occurs both as individual grains and as fragments. Some brown and colourless grains are well rounded. Six single zircons were analyzed. Two brown grains and a colourless to brown overgrowth separated from a colourless core provide discordant data with ^{207}Pb/^{206}Pb ages between 2718.5 and 2714.9 Ma (Figure 5.3a). A colourless prism and 2 colourless grain fragments yield concordant data with ^{207}Pb/^{206}Pb ages of 2708.4±3.1 Ma, 2701.6±1.9 Ma and 2695.6±3.0 Ma. The epiclastic unit was, therefore, deposited sometime after 2695.6±3.0 Ma.

A sample of thinly bedded, turbiditic, sandstone-siltstone was also collected from the outcrop immediately to the south of the conglomerate sample (*see* Figure 5.1, sample H). Based on facing directions in the 2 outcrops, the sandstone-siltstone underlies the conglomerate unit. The modest zircon yield consists of prismatic to rounded, colourless to brown grains of variable quality ranging from equant to 4:1. Longer aspect ratio zircons are typically the most euhedral and average grain size is relatively small. A representative zircon population was gently air abraded. ^{207}Pb/^{206}Pb ages for 6 analyses covering the variety of grain types range from circa 2747 Ma to 2703.1±1.6 Ma (Figure 5.3b). The latter result provides a maximum age of deposition of the sedimentary unit.

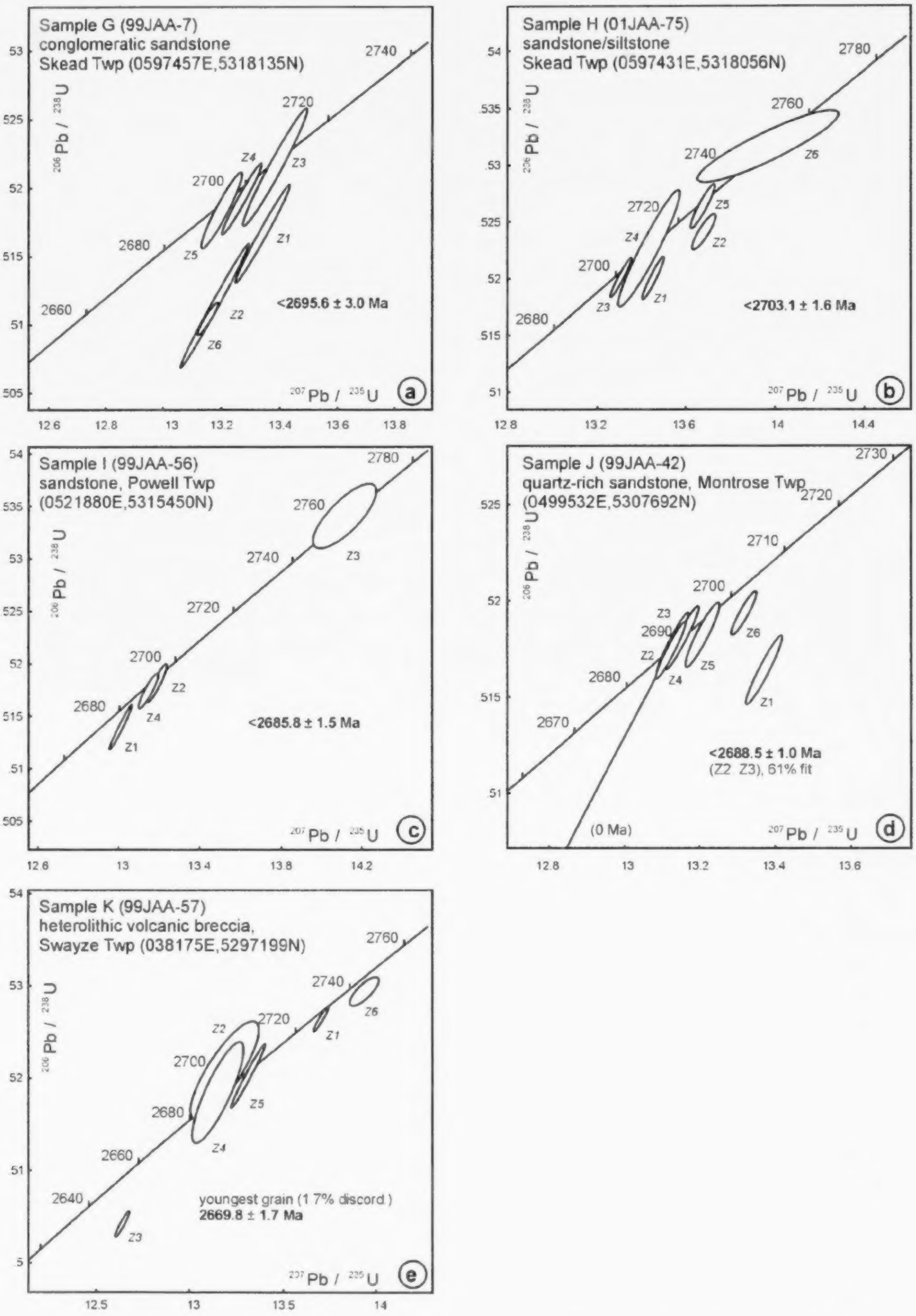

Figure 5.3. Concordia diagrams with U/Pb analyses for zircon. Ellipses indicate the 2σ uncertainty.

The above results indicate that the turbiditic sandstones interbedded with oxide iron formation from the Larder Lake area were deposited after 2674.3±3.7 Ma and, indeed, are part of the Timiskaming assemblage as was originally proposed by Hyde (1980). In addition, the presence of zircons with ages of 2684±4 Ma may suggest that some of the detritus was derived from slightly older nonmarine association units located west and north of this facies. The above maximum depositional age corresponds well with an age of 2673±2 Ma for a volcaniclastic unit interbedded with turbidites in the Timiskaming Group along strike to the east in Quebec (Davis 2002). Therefore, it is likely that much of the northern part of the "Hearst assemblage" (Jackson, Fyon and Corfu 1994) should be included within the Timiskaming assemblage (*see* Figure 5.1).

Our geochronological data from the southern part of the "Hearst assemblage" (Jackson, Fyon and Corfu 1994) indicate a maximum deposition age of 2695.6±3.0 Ma. This indicates that the sedimentary units unconformably overlie, and are probably structurally interleaved with, the adjacent Larder Lake Group volcanic rocks of the Tisdale assemblage (2710 to 2703 Ma) (Ayer et al. 2002). This interpretation differs from the interpretation of Jensen and Langford (1985), who indicated that these sedimentary units were coeval with the Larder Lake Group volcanic rocks. The maximum deposition age is significantly older than the Timiskaming-age nonmarine and resedimented associations in the Kirkland Lake and Larder Lake areas, which suggests the southern turbiditic unit could be correlative with the Porcupine assemblage. In addition, the wide spectrum of older detrital zircon ages in these units encompasses a number of the underlying volcanic assemblages including the Pacaud (i.e., 2750 to 2745 Ma), the Kidd–Munro (2719 to 2712 Ma), the Tisdale (2710 to 2703 Ma) and the Blake River (2700 to 2697 Ma).

Our results also confirm the geochemically based interpretation of Legault and Hattori (1994), who indicated that the northern turbidites are geochemically similar to the nonmarine sedimentary rocks, both of which were modelled as comprising about 80% quartz monzodiorite, 20% trachyte and 20% tholeiite. Thus, both the geochemical and the geochronological data indicate a similar provenance for the 2 northern associations. On the other hand, the results of Legault and Hattori (1994) indicated that the southern turbidites have significantly different chemical patterns indicating provenance from a terrain estimated to contain about 70% mafic volcanics, 18% komatiite and 12% rhyolite, without any evidence of input from alkalic magmatic sources.

Matachewan Area

A unit of conglomerate and cross-bedded sandstone, locally associated with turbiditic sedimentary rocks, extends west from Matachewan into the Halliday area north of the CLLF (*see* Figure 5.1). Jensen (1995) assigned this unit to the Timiskaming Group. The youngest detrital zircons, from sandstone interbedded with conglomerate in northeastern Halliday Township, indicate a maximum depositional age of 2690±3.0 Ma (Ayer et al. 2002). Turbiditic sedimentary units occur within the central, probably uppermost part of the unit in Midlothian Township, and turbiditic sedimentary units also occur to the north in Powell and Montrose townships (not shown on Figure 5.1), which Jensen (1995) assigned to a pre-Timiskaming assemblage sedimentary sequence.

In order to constrain the age of these northern units, the authors sampled thickly bedded sandstone from the sedimentary unit located north of Matachewan (*see* Figure 5.1, sample I). Detrital zircons from the sample are mainly equant to 2:1, brown and colourless grains of variable size. Most brown grains are euhedral and multifaceted, whereas colourless grains range from euhedral to anhedral. There are also some relatively small 3:1 to 4:1 euhedral colourless and brown prisms. Few, if any, of the zircons show evidence of detrital pitting, suggesting that they may represent locally derived detritus. Four single grains have ages that range from 2685.8±1.5 Ma for a nearly concordant brown prism to 2757±12 Ma for a small euhedral 3:1 prism (Figure 5.3c). Two grains have overlapping concordant ages of 2692.3±2.7 Ma and 2695.2±2.4 Ma.

A second sample was collected from the dominantly fine-grained turbiditic sedimentary unit in southern Montrose Township (*see* Figure 5.1, sample J). The sample was collected from a 1.3 m wide, medium- to coarse-grained, north-facing, quartz-rich sandstone bed within a larger package of interbedded sandstone, siltstone and conglomerate exhibiting both normal and reverse grading. Abundant detrital zircons were recovered from the sandstone and most were small, euhedral, light brown, 2:1 prisms many with minor tip overgrowths of presumed metamorphic origin. Larger colourless to brown grains and prism fragments are also present. A range of grain types were abraded with care being taken to exclude grains with tip overgrowths, and to remove any thin, optically invisible overgrowths that might be present. Six single grain analyses are concordant to moderately discordant with $^{207}Pb/^{206}Pb$ ages ranging from 2723 to 2688 Ma (Figure 5.3d). Discordance is greater with increasing age. Fractions Z2 and Z3 overlap on concordia and indicate a maximum deposition age of 2688.5±1.0 Ma.

The data suggest that these sedimentary units were deposited sometime after 2688.5±1.0 Ma to 2685.8±1.5 Ma and, thus, could belong to either the Porcupine or the Timiskaming assemblages given the new time limits established for these assemblages as discussed above. Future petrographic and geochemical studies, similar to those of Legault and Hattori (1994) for the sedimentary units in the Larder Lake area, may help to resolve the issue.

Swayze Area

Mapping and geochronological work in the Swayze area (*see* Figure 5.1) by Heather (1998) revealed progressively upward-facing stratigraphy from the core of the Woman Lake antiform, adjacent to the southwestern lobe of the Kenogamissi batholith, northwest to the centre of the Brett Lake synform. Previously, the youngest unit detected in this portion of the stratigraphic succession was the Brett Lake Formation consisting of a mixed package of felsic to intermediate pyroclastic and volcaniclastic rocks with ages of 2697±1 Ma and 2695±2 Ma, which was assigned to the Blake River assemblage (Ayer et al. 2002).

A volcanic breccia, near the core of the Brett Lake syncline (*see* Figure 5.1, sample K), was sampled to test the age of the uppermost part of this stratigraphic section. The volcanic breccia consists of angular and subrounded fragments, locally with flow laminated red and green feldspar porphyry clasts, set in a gritty matrix. The shoshonitic geochemical signature of this unit (J.A. Ayer, OGS, unpublished data, 1999) suggests that it may be of Timiskaming age.

Zircons in the least paramagnetic separate are mainly colourless and range from rounded grains and 2:1 stubby prisms to 4:1 slender prisms. Less abundant brown grains have a similar morphological range. Most zircons are euhedral or subhedral, and only a few appear to be pitted from sedimentary transport. Data for 6 single zircons indicate a range of detrital ages (Figure 5.3e). The oldest grain is a light brown equant prism and provided an age of 2750.2±6.4 Ma. A light brown prism fragment is discordant, but appears to be the youngest grain (assuming recent Pb loss) with a $^{207}Pb/^{206}Pb$ age of circa 2670 Ma. Two small, colourless zircons yield overlapping, but imprecise, ages of 2686±13 Ma and 2689±10 Ma. Two additional grains have ages of 2703.6±2.0 Ma and 2731.8±1.5Ma.

These data indicate that the volcanic fragmental unit in the core of the Brett syncline in Swayze Township (*see* Ayer and Trowell (2002) for a more detailed map) is most likely of Timiskaming age and contains a wide spectrum of ages from underlying assemblages including the Pacaud (2750to 2745 Ma), the Deloro (2730 to 2725 Ma), the Tisdale (2710 to 2703 Ma) and the Blake River (2701 to 2697 Ma). The authors suggest that these are largely inherited zircons incorporated from underlying strata rather than sedimentary-derived detrital grains. Interestingly, these inherited ages exclude those of the Stoughton–Roquemaure (2723 to 2720 Ma) and the Kidd–Munro (2719 to 2710 Ma) assemblages. This observation is consistent with the hypothesis of Ayer et al. (2002) that a major stratigraphic gap exists between the Deloro and Tisdale assemblages, located between the PDF and CLLF–Ridout fault systems, and may be the result of early extensional movements.

Table 5.2. Whole-rock neodymium isotopic data.

Assemblage or Intrusion	Other Information	Rock Description	Easting (m) [1]	Northing (m) [1]	Age (U/Pb with 2σ error)	ε Nd (CHUR)T
Porcupine assemblage	Krist Formation	dacitic bedded tuff	476300	5365940	2689±1	2.8
Porcupine assemblage	Indian Lake Group	massive felsic flow	499750	5272535	2687±2	2.5
Porcupine assemblage	Natal Group	andesite flow	493454	5278668	2687	2.2
Millie Creek stock		hornblende monzonite	498808	5279430	2685	2.9
unnamed intrusion		fine-grained syenite	488038	5274695	2685	3.0
Kenogamissi batholith	southwestern lobe	biotite granodiorite	411475	5295861	2700	2.9
Kenogamissi batholith	southwestern lobe	hornblende diorite	414555	5287174	2684±2	2.3
Kenogamissi batholith	southwestern lobe	biotite-hornblende tonalite	414207	5288221	2742±1	2.9
Kenogamissi batholith	southwestern lobe	diorite	417644	5295505	2684	2.6
Kenogamissi batholith	southwestern lobe	biotite-hornblende tonalite	414570	5279524	2742±1	2.6
Kenogamissi batholith	southwestern lobe	biotite granodiorite	413503	5283989	2700±1	2.0
					average	**2.6**

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[1] UTM co-ordinates are NAD83, Zone 17.

NEODYMIUM ISOTOPES

Eleven samples were analyzed for neodymium isotopes (Table 5.2). The samples were selected to extend the age range of previously analyzed SAGB samples reported in Ayer et al. (2002) and to compare the isotopic ratios of the volcanic rocks and coeval intrusions. Three of the samples are from the calc-alkalic volcanic rocks in the Porcupine assemblage (2688 Ma); 1 from the Krist Formation in Timmins; 1 from the Natal Group; and 1 from the Indian Lake Group, the latter 2 of which are from the Shining Tree area. Two samples of intrusions, which are interpreted to be coeval with the Porcupine assemblage, were analyzed from the Shining Tree area. These samples consist of a monzonite from the Millie Creek stock in south-central Knight Township; and a syenite sample from an unnamed intrusion in southwestern Knight Township. Six of the samples were analyzed to represent 3 different ages of intrusions in the southwestern lobe of the Kenogamissi batholith: tonalite (2742 Ma), granodiorite (2700 Ma) and diorite (2685 Ma).

The $\varepsilon_{Nd}(T)$ values were calculated using the U/Pb ages of the same samples, or the ages of precisely dated rocks in adjacent units (*see* Table 5.2). The $\varepsilon_{Nd}(T)$ values vary between +2.0 and +3.0, with an average value of +2.6. This compares favourably with the average of +2.7 reported in Ayer et al. (2002). Figure 5.4 compares this data with data from Ayer et al. (2002) and a number of other sources. This comparison shows remarkably uniform positive $\varepsilon_{Nd}(T)$ values from 2740 Ma to 2680 Ma for rocks of different chemical affinities and provides a comparison to the Neoarchean depleted-mantle neodymium isotopic evolution curve (*see* Figure 5.4: DM; DePaolo 1988). The data indicate that there was no major contamination by significantly older continental crust (i.e., >100 million years) in the magma source areas throughout the magmatic evolution of the SAGB.

DISCUSSION AND CONCLUSIONS

The change in the age range for the Porcupine assemblage to 2690–2680 Ma and for the Timiskaming assemblage to 2680–2674 Ma fits well with new geochronological data from the sedimentary units in the SAGB in Quebec (Davis 2002). However, it requires change in the affiliations of some of the units on Figure 5.1 (compare with Ayer et al. 2002, Figure 1). Stratigraphic classification of these late tectonic units is quite difficult because the facies relationships are not as clear as was thought by some previous workers (i.e., early marine turbidites followed by subaerial conglomerates and sandstones) (e.g., Mueller, Donaldson and Doucet 1993; Jackson, Fyon and Corfu 1994). Also, using detrital zircons to estimate deposition ages for sedimentary rocks is typically less definitive than the magmatic zircon ages from volcanic rocks, as the former will only provide the maximum age for deposition for the sediments.

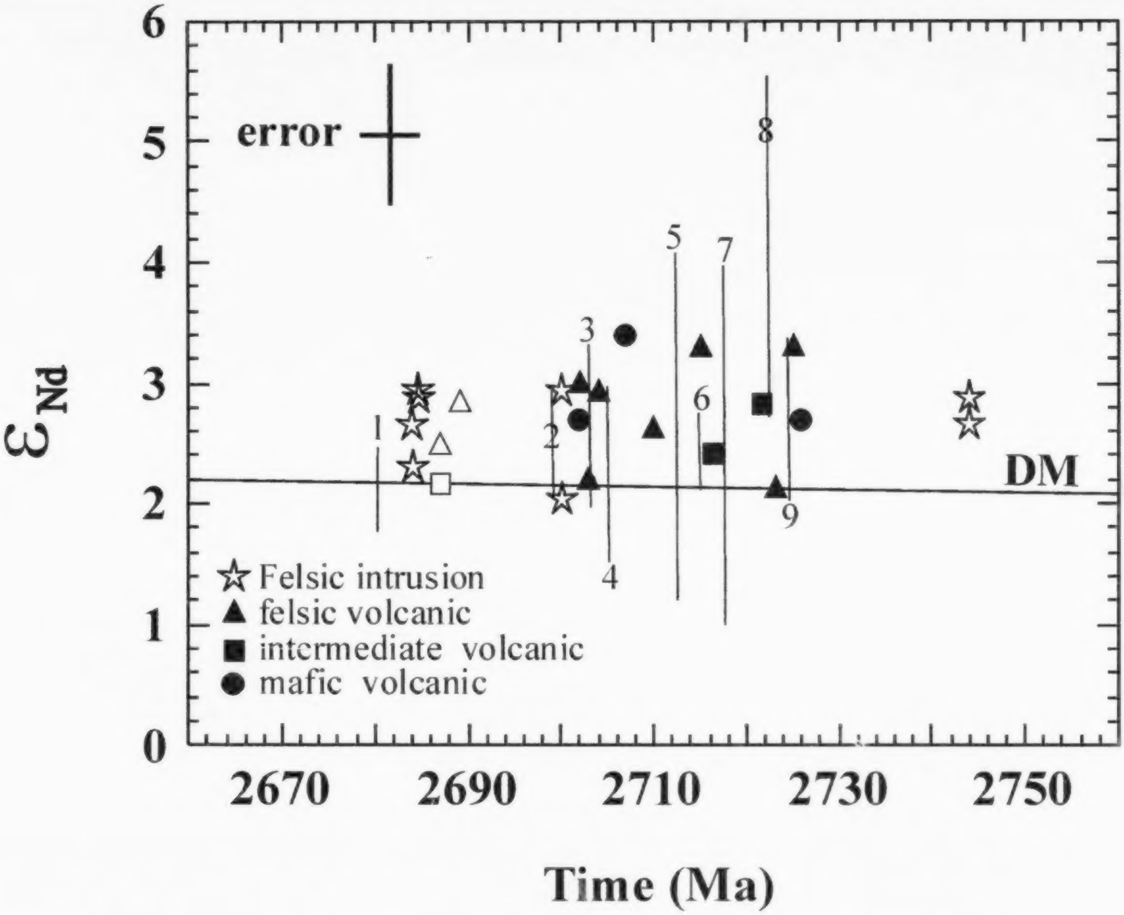

Figure 5.4. Age versus ε_{Nd} (T) for samples (open symbols) reported in Table 5.2 along with the samples (solid symbols) reported in Ayer et al. (2002) and the range of values from previously reported Abitibi greenstone belt volcanic samples. 1, Timiskaming volcanic rocks, Kirkland Lake (Ben Othman et al. 1990); 2, Mine Series volcanics, Noranda, Québec (Vervoort, White and Thorpe 1994); 3, komatiites and tholeiites, Newton Township (Cattell, Krogh and Arndt 1984); 4, mafic volcanics, Kamiskotia (Barrie and Shirey 1991); 5, Kidd Creek rhyolites (Prior et al. 1999); 6, Kidd Creek komatiites and tholeiites (Barrie et al. 1999); 7, komatiites from Munro Township (Walker, Shirey and Stecher 1988); 8, komatiites and tholeiites from Stoughton–Roquemaure Group, Québec (Dostal and Mueller 1997); 9, mafic and felsic volcanics, Matagami, Québec (Vervoort, White and Thorpe 1994). DM, depleted mantle evolution curve from DePaolo (1988).

For example, Ayer et al. (2002) misinterpreted the Indian Lake and Natal groups in the Shining Tree area as Timiskaming assemblage. We now include both of these units within the Porcupine assemblage since the volcanic rocks in the basal portions of both groups have magmatic ages of circa 2688 Ma. The volcanic rocks are also conformably succeeded by sedimentary rocks, which is an age and facies relationship analogous to the Krist and Beatty formations of the Porcupine assemblage near Timmins. We are currently uncertain if the turbidite-dominated sequences in Powell and Montrose townships and the conglomerates and sandstones of the Ridout Group (Heather 1998) in the Swayze area are correlative with the Porcupine or Timiskaming assemblages. Further petrological, geochemical and geochronlogical studies will be required to more precisely identify the affiliations of these units.

The distribution of the late tectonic units is economically important in identifying the locations of major crustal breaks as there is clearly a spatial and genetic correlation of gold mineralization to these faults. We feel that the presence of Porcupine assemblage felsic volcanic rocks conformably overlain by turbidites in the Shining Tree area is quite analogous to the Hollinger–McIntyre part of the Timmins camp where there is evidence for a "porphyry-like" spatial association with early gold mineralization (Brisbin and Pressacco 1999; Gray and Hutchinson 2001). We also suggest that further gold exploration of the less extensively explored areas with Porcupine and/or Timiskaming assemblage rocks may be fruitful. For example, the Matachewan, Shining Tree and Swayze areas contain these assemblages associated with regional faults, as well as a significant number of associated gold occurrences, extensive zones of hydrothermal alteration and high level calc-alkalic to alkaline intrusions, which may have a "porphyry-like" gold association.

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6. Project Unit 02-003. Fertile and Peraluminous Granites and Related Rare-Element Pegmatite Mineralization, Superior Province, Northeastern Ontario

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INTRODUCTION

This project represents a continuation of the work initially conducted under Operation Treasure Hunt (Breaks, Selway and Tindle 2001). Focus of the current project is on the north-central and northeastern parts of the Superior Province where little existing data are available on the field characteristics, mineralogical and geochemical features of peraluminous pegmatitic granites and rare-element mineralization (Figure 6.1).

Several significant results emerged from the current study:

- follow-up examination of the tantalum-rich, North and South Aubry pegmatites and reclassification as complex-type, spodumene-subtype
- investigation of the highly fractionated South Aubry lepidolite boulder. The boulder contains wodginite and pollucite, which are ore minerals in the Tanco pegmatite mine, southeastern Manitoba.
- investigation of the newly discovered Swole Lake lepidolite-spodumene pegmatite and verification as highly evolved with respect to exclusive presence manganotantalite that is virtually free of iron relative to manganese
- significant rare-element (rubidium, lithium, cesium, tin, tantalum and niobium) lithochemical dispersion halo detected in Onaman–Tashota terrane on North Jackfish Road and near Crescent Lake pegmatite group
- detailed investigation of the Superb Lake rare-element pegmatite, north of Nakina and consequent classification as complex-type and spodumene-subtype
- discovery of new rare-element pegmatite mineralization of the beryl-type: on Ketchican Road, Armstrong area; Abamasagi Road, Nakina area; and Shetland Township, Hearst area
- detailed investigation of the Lowther Township rare-element pegmatite in the Hearst area and consequent classification as complex-type and lepidolite- to spodumene-subtype.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.6-1 to 6-42.

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Unless otherwise noted, all analytical data presented in this report were provided by the Geoscience Laboratories, Ontario Geoservices Centre, Sudbury. All microprobe analyses of mineral phases were conducted by A.G. Tindle at The Open University, Milton Keynes, United Kingdom.

Locations are provided in Universal Transverse Mercator (UTM) co-ordinates in North American Datum 1983 (NAD83).

WABIGOON–ENGLISH RIVER SUBPROVINCAL BOUNDARY ZONE

This boundary zone has rare-element mineralization over a 130 km strike length between Linklater Lake east to Superb Lake near Nakina (Figure 6.2).

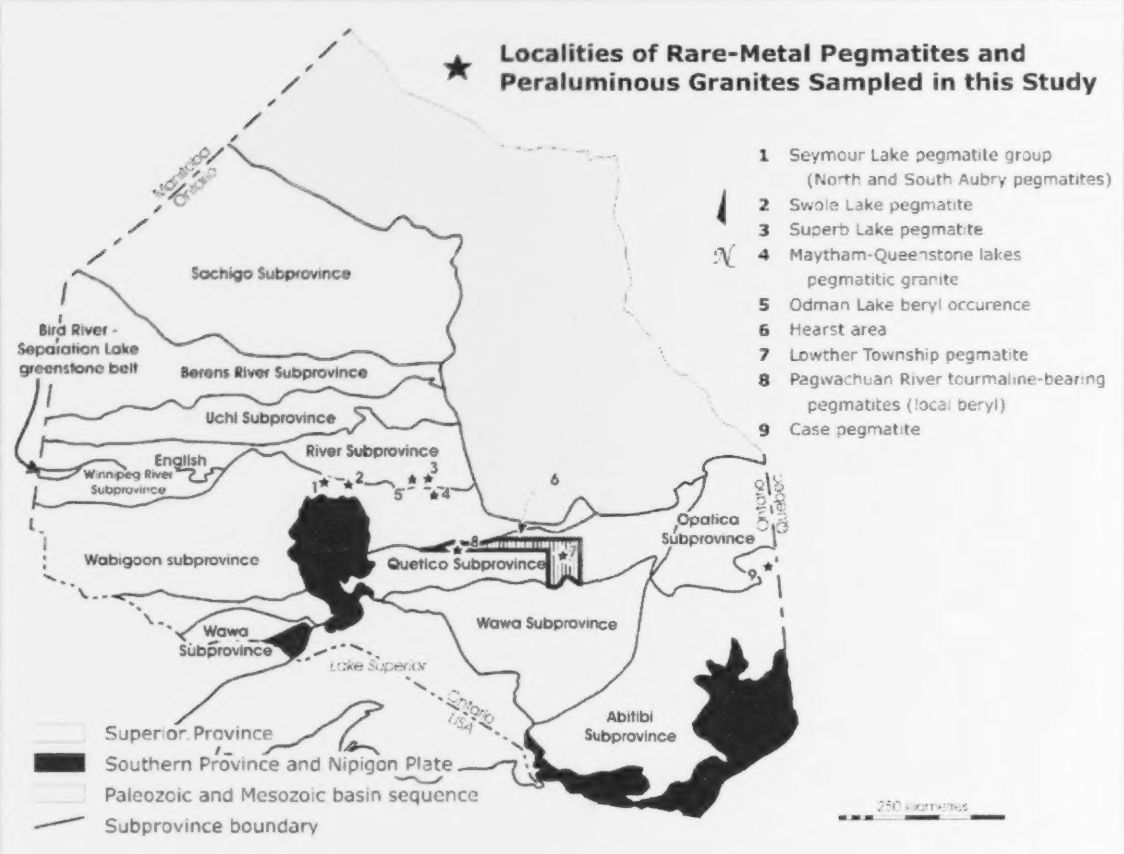
★ Localities of Rare-Metal Pegmatites and Peraluminous Granites Sampled in this Study
1 Seymour Lake pegmatite group (North and South Aubry pegmatites)
2 Swole Lake pegmatite
3 Superb Lake pegmatite
4 Maytham-Queenstone lakes pegmatitic granite
5 Odman Lake beryl occurence
6 Hearst area
7 Lowther Township pegmatite
8 Pagwachuan River tourmaline-bearing pegmatites (local beryl)
9 Case pegmatite
N
Manitoba
Ontario
Sachigo Subprovince
Bird River - Separation Lake greenstone belt
Berens River Subprovince
Uchi Subprovince
English River Subprovince
Winnipeg River Subprovince
Wabigoon subprovince
Quetico Subprovince
Opatica Subprovince
Ontario
Quebec
Wawa Subprovince
Lake Superior
Ontario
USA
Abitibi Subprovince
Superior Province
Southern Province and Nipigon Plate
Paleozoic and Mesozoic basin sequence
Subprovince boundary

Figure 6.1. Location of peraluminous pegmatitic granite masses and rare-element pegmatite mineralization examined in this study.

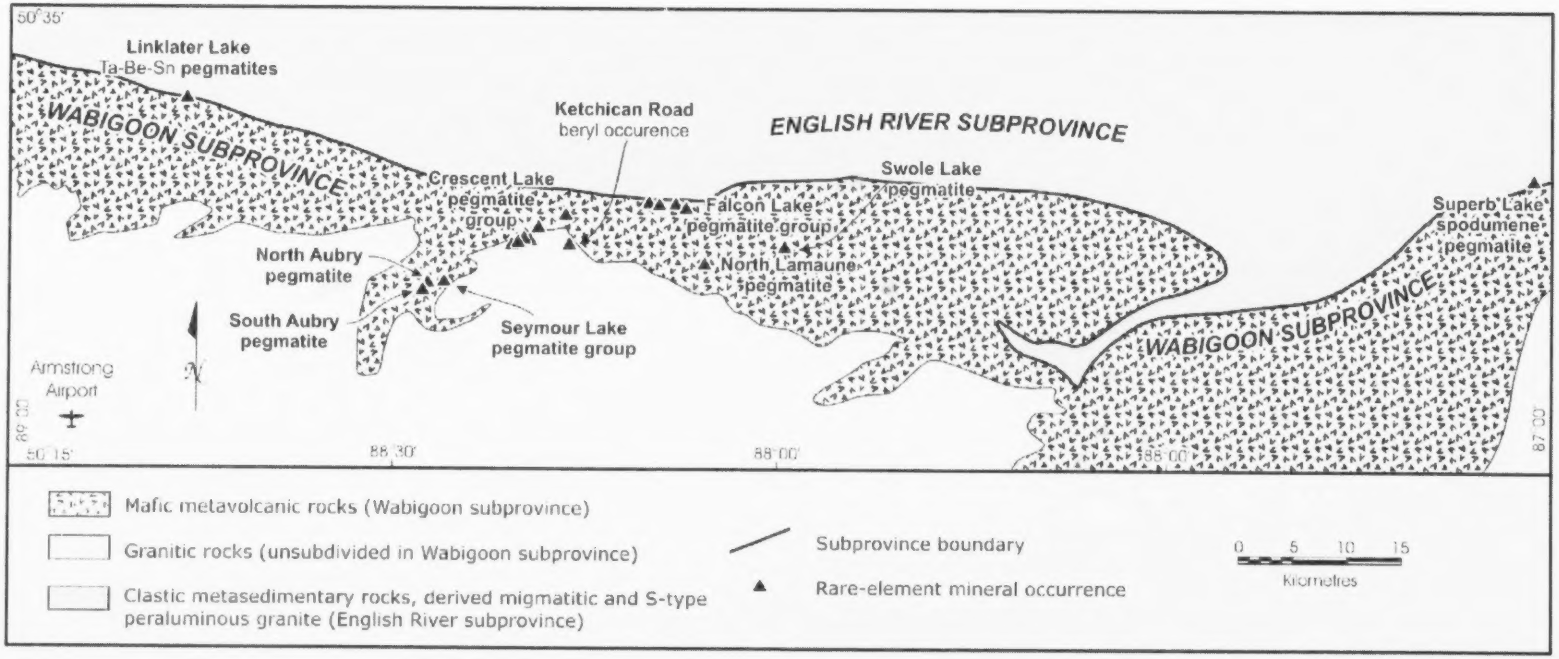
50°35'
Linklater Lake
Ta-Be-Sn pegmatites
WABIGOON SUBPROVINCE
Ketchican Road
beryl occurence
ENGLISH RIVER SUBPROVINCE
Crescent Lake
pegmatite
group
Swole Lake
pegmatite
Falcon Lake
pegmatite group
North Lamaune
pegmatite
Superb Lake
spodumene
pegmatite
North Aubry
pegmatite
South Aubry
pegmatite
Seymour Lake
pegmatite group
WABIGOON SUBPROVINCE
N
Armstrong
Airport
89°00'
50°15'
88°30'
88°00'
88°00'
87°00'
Mafic metavolcanic rocks (Wabigoon subprovince)
Granitic rocks (unsubdivided in Wabigoon subprovince)
Clastic metasedimentary rocks, derived migmatitic and S-type peraluminous granite (English River subprovince)
Subprovince boundary
Rare-element mineral occurrence
0
5
10
15
Kilometres

Figure 6.2. General geological location of rare-element mineralization situated in the English River–Wabigoon subprovincial boundary zone in the Armstrong–Nakina area (geology generalized *after* Parker and Stott 1988).

North and South Aubry Pegmatites

The North and South Aubry spodumene-subtype pegmatites are located 59 km northeast of Armstrong and 2.7 km west of Seymour Lake along a prominent ridge that has approximately 100 m of local relief. The North and South Aubry pegmatites intrude mafic metavolcanic rocks of the Wabigoon Subprovince. The North and South Aubry pegmatites are a series of stacked horizontal sills which dip shallowly to steeply east. The main body of the North Aubry pegmatite ranges in true thickness from 10 to 28 m over a strike length of 125 m (Linear Resources Inc., News Release, August 26, 2002, www.linearresources.com). The main body of the South Aubry pegmatite has an estimated true thickness of 15 to 16 m over a strike length of 95 m (Linear Resources Inc., News Release, August 26, 2002).

The North Aubry pegmatite is characterized by large spodumene crystals (up to 1.4 m long), coarse manganotantalite (up to 5 cm) and abundant blocky potassium feldspar. The South Aubry pegmatite is characterized by plumose quartz + muscovite intergrowths, coarse green beryl (up to 46 by 34 cm) and abundant albite. The most obvious difference between the North and South Aubry pegmatites is that muscovite is more abundant in South Aubry than in North Aubry.

Recent exploration for tantalum by Linear Resources Inc. has exposed 7 trenches over the North Aubry pegmatite and 3 trenches over the South Aubry pegmatite (Figure 6.3). The trenches are areas where a bulldozer has removed the overburden to expose the outcrop. Trench SA-5 (*see* Figure 6.3) is labelled by Linear Resources Inc. as South Aubry, but the geology indicates that it is part of the North Aubry pegmatite. Linear Resources Inc.'s SA-4 trench (*see* Figure 6.3) is actually a lepidolite-rich boulder, which resembles the Swole Lake pegmatite rather than the North and South Aubry pegmatites.

Linear Resources Inc. are also conducting a diamond-drilling program to delineate the pegmatites and to define grade and tonnage of the tantalum mineralization. The stacked nature of the pegmatites was verified by this drilling program (Linear Resources Inc., News Release, www.linearresources.com, August 26, 2002). Several hidden pegmatites were intersected at depth in the diamond drilling; the widest of which is a spodumene pegmatite with a 4 to 5 m true thickness situated approximately 50 m below the western margin of the North Aubry pegmatite. Another 4 to 5 m thick, spodumene pegmatite was intersected by diamond drilling about 25 to 40 m below the South Aubry pegmatite. Stacked pegmatites with estimated true thicknesses from less than 1 to 8 m were also intersected below the South Aubry Trench SA-5 (*see* Figure 6.3).

Preliminary geology of the North and South Aubry pegmatites is described by Breaks, Selway and Tindle (2001) and bulk and mineral analyses for samples collected from 5 trenches at North Aubry and 3 trenches at South Aubry are described by Breaks, Selway and Tindle (in press). This summer's field work focussed on the geology of trenches not previously examined by Breaks, Selway and Tindle (in press) and divided the North Aubry pegmatite into pegmatite zones.

GEOLOGY OF THE NORTH AUBRY PEGMATITE

The mafic metavolcanic host rocks are massive and pillowed. The host rocks have been metamorphosed to amphibolite grade producing local calc-silicate segregations of chlorite-epidote-quartz-carbonate. Rare-element-rich fluids (i.e., rubidium, cesium, lithium and boron) flowed from the pegmatite melt into the host rocks to produce biotite, tourmaline and holmquistite metasomatic aureoles. The biotite metasomatism is ubiquitous, whereas tourmaline aureoles have only been exposed in trenches NA2-3, NA-5 and holmquistite has only been exposed in trench NA-5 (*see* Figure 6.3). The biotite has a composition of siderophyllite-zinnwaldite and is rich in lithium, rubidium and cesium. These rare-elements decrease further into the host rock away from the contact with the pegmatite. The host rocks may be bright blue due to the high concentration of randomly oriented holmquistite (lithium-rich amphibole) needles. A 20 cm long channel sample across one of the holmquistite-rich mafic metavolcanic pillows was analyzed at 7519 ppm Li indicating significant metasomatism.

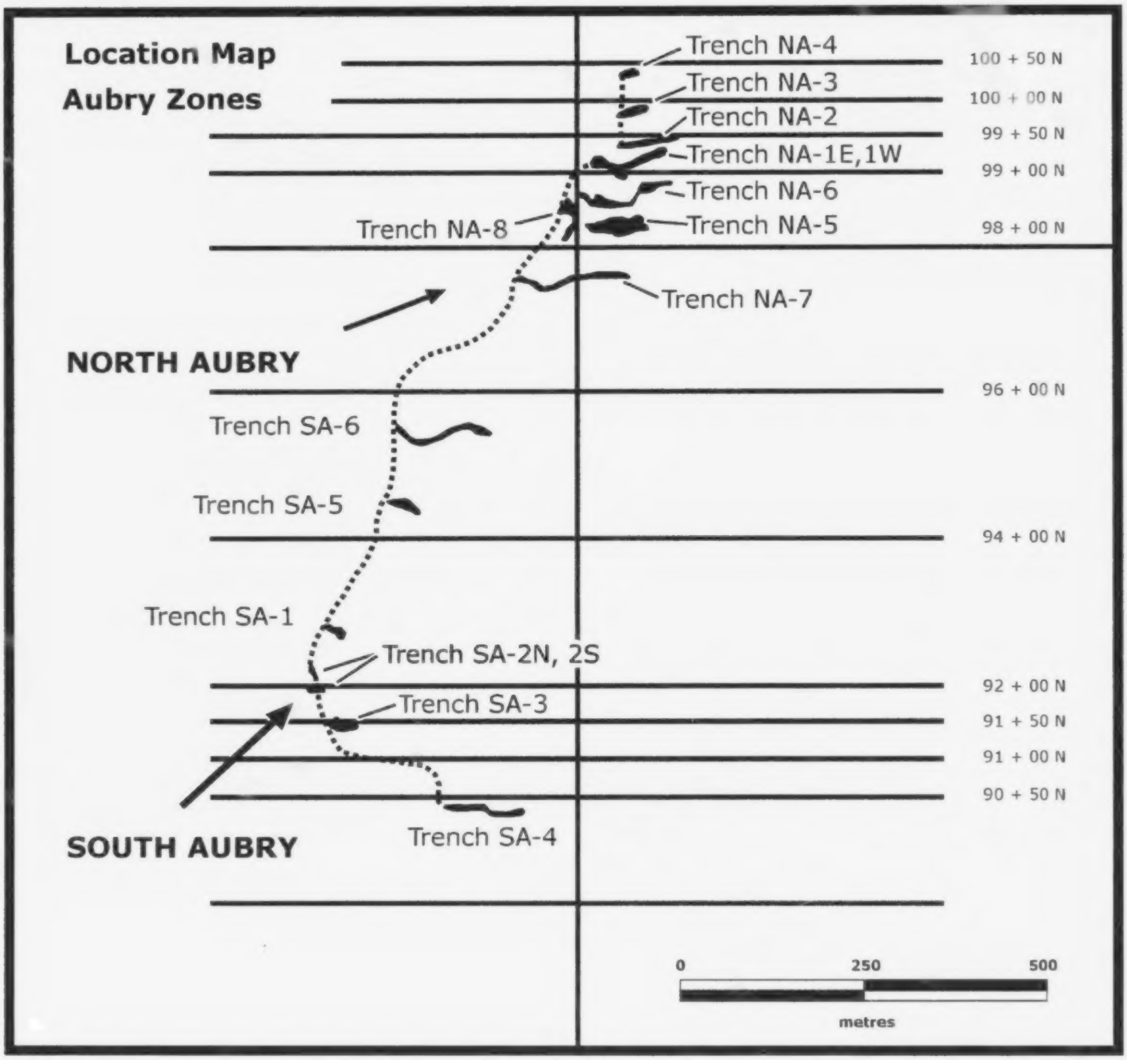
Location Map
Aubry Zones
Trench NA-4
Trench NA-3
Trench NA-2
Trench NA-1E,1W
Trench NA-6
Trench NA-8
Trench NA-5
Trench NA-7
100 + 50 N
100 + 00 N
99 + 50 N
99 + 00 N
98 + 00 N
NORTH AUBRY
96 + 00 N
Trench SA-6
Trench SA-5
94 + 00 N
Trench SA-1
Trench SA-2N, 2S
Trench SA-3
92 + 00 N
91 + 50 N
91 + 00 N
90 + 50 N
Trench SA-4
SOUTH AUBRY
0
250
500
metres

Figure 6.3. Map of the North Aubry and the South Aubry trenches *from* Linear Resources Inc. (www.linearresources.com). Trenches NA-7, NA-8 and SA-6 were not accessible during 2002 field season. Trenches NA-7 and SA-6 exposed mafic metavolcanic rocks only.

The North Aubry spodumene-subtype pegmatite is complexly zoned and can be simplified into 10 pegmatite zones, based on mineral assemblage. From outermost to innermost zone, these zones are

1. thin quartz-rich border zone (~1 cm thick) (only in trenches NA2-3, NA-2, NA5-6)
2. outer sodic zone (aplite or cleavelandite), aplite dikes (only in trench NA-4), aplite + silver muscovite zone (only in trench NA-2), aplite pods (only in trench NA-2), fluorapatite-cleavelandite zone (only in trench NA-6), miarolitic cavities (only in trench NA-4)
3. quartz-muscovite zone
4. muscovite pods (only in trench NA-2)
5. quartz pods
6. potassium feldspar zone
7. albite-spodumene zone (aplite or cleavelandite)
8. potassium feldspar-spodumene zone (most abundant zone)
9. inner core zone: coarse tantalite, pink beryl, cleavelandite, spodumene (found only in trench NA-5), highly fractionated zone
10. corona zone (found only in trench NA-5): highly fractionated zone

The thin quartz-rich border zone (1) is commonly only 1 cm thick, but, in trenches NA-2 and NA-3, it is much thicker. Trenches NA-2 and NA-3 contain a black prismatic tourmaline cluster (19 cm long) surrounded by feldspar + fluorapatite. This is the largest cluster of tourmaline in the pegmatite.

In order to simplify the pegmatite zoning sequence, aplite and cleavelandite are grouped together, as they represent 2 different textures for albite. Aplite is very fine-grained, sugary equant albite and cleavelandite is platy coarse-grained albite. In the northern part of the pegmatite (trenches NA-4, NA2-3, NA-6), the outer sodic zone contains aplite and the albite-spodumene zone contains cleavelandite, whereas in the southern part of the pegmatite (trenches NA5-6, NA-5, SA-5), the outer sodic zone contains cleavelandite and the albite-spodumene zone contains aplite.

Throughout the North Aubry pegmatite, the outer sodic zone (2) contains abundant quartz and minor fine-grained tantalum-oxide minerals and fluorapatite. In trench NA-4, the outer sodic zone contains minor amounts of garnet, molybdenite, green muscovite and white beryl. This is the only occurrence of molybdenite in the Aubry pegmatites. In trenches NA-2 and NA-3, the outer sodic zone contains minor amounts of black tourmaline. In trench NA-6, the outer sodic zone is up to 30 cm wide and consists of aplite with minor fine-grained biotite and rare spodumene altered to biotite + hematite. The presence of spodumene in the outer sodic zone in trench NA-6 probably represents a transition between the outer sodic zone and the potassium feldspar-spodumene zone. In the eastern end of trench NA-5, the outer sodic zone contains minor black tourmaline, whereas in trench NA5-6, black tourmaline occurs in fractures.

Trench NA-4 contains a fine-grained reddish aplite dike (0.3 to 0.6 m thick) in the mafic metavolcanic rocks near the east end of the trench. A bulk sample of the aplite shows elevated tantalum contents (278 ppm Ta). Near the eastern end of trench NA-2, primary aplite pods are enveloped in a quartz pod with notable concentrations of black manganocolumbite crystals (~1 cm long) along the contact between the aplite and quartz pods.

Miarolitic cavities, up to 5 by 6 cm in size, occur in cleavelandite-rich aplite in trenches NA-4 and NA-5 and are mainly lined with cleavelandite crystals with minor muscovite and tourmaline, all of which are coated by a drusy film of hematite. The miarolitic cavities are located close to the contact with the mafic metavolcanic host rocks and contain coarse-grained black tourmaline (1.5 cm long). A few inches away from the tourmaline-bearing miarolitic cavity is a more fractionated cavity with tiny primary microlite inclusions in quartz adjacent to a large white cesium-rich beryl (0.5 to 2.3 weight % Cs_2O) and minor fluorapatite in cleavelandite.

The intermediate quartz-coarse muscovite zone (3) is relatively abundant throughout the pegmatite and the zoning sequence is usually host rock–outer sodic zone–quartz-muscovite zone–potassium feldspar zone or potassium feldspar-spodumene zone. This zone contains minor oxide minerals in trench NA-3, and minor fluorapatite and white beryl (3.5 by 2.5 cm) in trench NA2-3. The quartz-muscovite zone is 10 cm wide in trench NA-6 and contains minor beryl. In trench NA5-6, the quartz-muscovite zone contains minor cleavelandite, spodumene and garnet, as it is located between the outer cleavelandite and the aplite-spodumene zones.

The muscovite pods (4) in trench NA-2 are up to 40 cm across and are enveloped by aplite or pink blocky potassium feldspar. The muscovite pods host oxide minerals and fluorapatite along their edges with 5% of interstitial quartz within the pods. Massive quartz pods (5) occur in trenches NA-3, NA2-3 and NA-2. In trench NA-3, the quartz pod contains 2 separate clusters: a) fine-grained green muscovite aplite and b) aplite with dark green spodumene and coarse-grained muscovite.

There are several variations on the potassium feldspar zone (6) due to the processes affecting the potassium feldspar. The blocky potassium feldspar is either unaltered, albitized or hematitized. The unaltered potassium feldspar zone in trench NA-3, contains blocky peach or white potassium feldspar, quartz, green muscovite and local spodumene. The quartz and muscovite contents in the potassium feldspar zone are variable to nil. For example, trench NA-6 contains a large area consisting of mono-mineralic white potassium feldspar. The presence of spodumene in the potassium feldspar zone is probably due to a transition to the potassium feldspar-spodumene zone. In trenches NA-3 and NA-2, the albitized blocky peach potassium feldspar is crosscut by veins (up to 10 cm wide) of aplite + fine-grained green muscovite. In trench NA-2, the albitized potassium feldspar zone contains rare green beryl (12 by 10 cm). At the east end of trench NA-3 and in trench NA2-3, the blocky potassium feldspar is red to pink due to hematization. The hematitized potassium feldspar zone contains minor orange lithiophilite ($LiMnPO_4$) with metallic black manganese-stained rims.

There are 2 variations on the albite-spodumene zone (7): a) cleavelandite-spodumene in trenches NA-4 and NA-6; and b) aplite-spodumene in trench NA5-6. The cleavelandite-spodumene zone (a) consists of abundant quartz, minor blue fluorapatite, green beryl, tantalum-oxide minerals and potassium feldspar. In trench NA-6, several coarse green spodumene (up to 1.4 m long) are aligned parallel to each other (oriented north) and perpendicular to the pegmatite–host rock contact, whereas finer spodumene crystals (~20 cm long) are randomly orientated. The coarse spodumene crystals are rimmed and invaded by an assemblage of muscovite, blue fluorapatite and green beryl only along the west side of each crystal. Both the coarse- and "finer" grained spodumene crystals may have muscovite inclusions. Locally, the blue fluorapatite in trench NA-6 is abundant and up to 2 cm long. The aplite-spodumene zone (b) consists of coarse-grained, green, spodumene with interstitial aplite and minor cleavelandite. The coarse green spodumene may be altered to red or black due to an influx of iron-rich fluids from the host rock. The interstitial aplite contains minor brown phosphates, fluorapatite, tantalum-oxide minerals and coarse muscovite.

The potassium feldspar-spodumene zone (8) is the most common zone in the pegmatite and is exposed in all of the trenches except for the north trench NA-4 and trench NA-5, which exposes the most fractionated pegmatite zone. This zone contains blocky white potassium feldspar, coarse-grained green spodumene, which may have abundant muscovite inclusions similar to zone (7), and common coarse-grained green beryl (up to 19 cm across). The minor constituents in this zone are quartz, muscovite, blue fluorapatite and tantalum-oxide minerals. This zone also has minor cleavelandite, and rare aplite and lithiophilite in trench NA-6. The presence of cleavelandite and aplite probably represent a transition from the potassium feldspar-spodumene zone to the cleavelandite-spodumene zone. In trench NA5-6, the beryl is pink, which is likely due to the close proximity of the inner core zone exposed in trench NA-5, which contains common pink beryl. In trench SA-5, the potassium feldspar-spodumene zone contains minor garnet, rare biotite and cleavelandite. In trench NA-6, several coarse green spodumene crystals (>2 m long) are aligned parallel to each other (oriented north) and perpendicular to the host rock–pegmatite contact (Photo 6.1a). The coarse spodumene crystals are rimmed and invaded by an assemblage of muscovite, blue fluorapatite and green beryl. The spodumene may have numerous muscovite inclusions. These textures are similar to that seen in the cleavelandite-spodumene zone in the same trench. The potassium feldspar-spodumene zone in trench NA-6 also contains blue fluorapatite and coarse tantalum-oxide minerals (up to 5.5 cm long by 1.5 cm wide) along the edge of waxy grey quartz pods.

The inner core zone (9) is only exposed in trench NA-5. The inner core zone consists of a coarse-grained green and white spodumene, which forms a box-work with interstitial white cleavelandite, quartz, pink cesium-rich beryl and coarse-grained equant manganotantalite (up to 5 cm). The inner core zone also contains minor amounts of purple lepidolite and blocky white potassium feldspar with inclusions of spodumene, and rare lithiophilite rimmed by black manganese staining.

The corona zone (10) displays the most interesting textures in the pegmatite. There are 2 types of coronas: a) several euhedral quartz crystals surrounded by radiating cleavelandite, and b) green spodumene rimmed by red hematite staining, which, in turn, is surrounded by radiating cleavelandite, green fluorapatite and tantalum-oxide needles (Photo 6.1b). The quartz-centred corona is spherical in shape, whereas the spodumene-centred corona mimics the overall prismatic shape of spodumene. Individual, very coarse-grained, spodumene crystals are not surrounded by cleavelandite in the inner core zone, but are surrounded by cleavelandite in the corona zone. These spodumene crystals are tapered with the wider end lying in the inner core zone and the narrow end lying in the corona zone which indicates that the inner core zone crystallized before the corona zone. Microprobe work to be completed during the spring of 2003 will verify the sequence of pegmatite zone crystallization by examining the composition of the tantalum-oxide minerals. Interstitial to both types of coronas is fine-grained purple lepidolite and albite.

GEOLOGY OF THE SOUTH AUBRY PEGMATITE

The South Aubry pegmatite, up to 50 m wide, is similar to the North Aubry pegmatite, as spodumene is the dominant lithium-bearing mineral. It differs from the North Aubry pegmatite in that muscovite is much more abundant. The South Aubry pegmatite can be divided into 4 zones: 1) aplite border zone, 2) plumose muscovite zone in trench SA-2, 3) beryl-spodumene zone in trench SA-1, and 4) albite-spodumene zone. Trench SA-3 reveals alternating albite-spodumene and plumose muscovite layers.

Similar to the North Aubry pegmatite, the mafic metavolcanic host rock has been metasomatized to produce a biotite-rich aureole. The biotite has a composition of siderophyllite-zinnwaldite and is enriched in lithium, rubidium, cesium and fluorine. The aplite border zone (1) contains quartz and minor blue fluorapatite, tantalum-oxides minerals and muscovite.

The South Aubry pegmatite largely consists of a plumose muscovite zone (2), characterized by impressive ovoid symplectites of quartz-muscovite with interstitial albite. These segregations, up to 1 m in diameter, contain approximately equal amounts of quartz and muscovite and are dominant in trench SA-2. Green beryl (up to 4 by 3 cm), blue fluorapatite and beige spodumene (30 by 2.5 cm) are minor in the plumose muscovite zone. Tantalum-oxide minerals and garnet rarely occur in the albite interstitial to the ovoids.

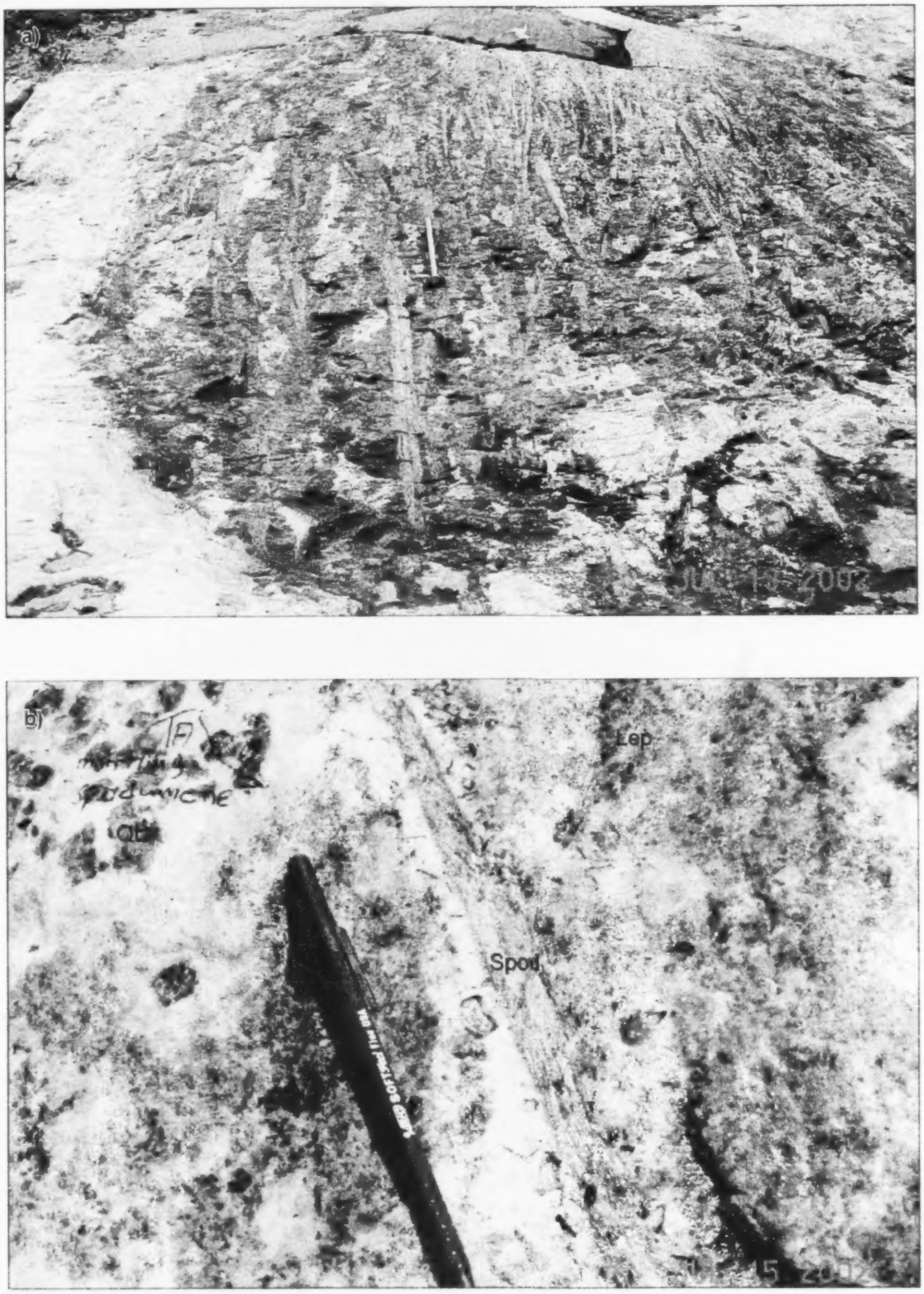

Photo 6.1. **a)** Very coarse spodumene crystals aligned parallel to each other and perpendicular to the contact with the mafic metavolcanic host rock; North Aubry trench NA-6. **b)** Quartz-centred and spodumene-centred coronas with interstitial lepidolite and albite; North Aubry trench NA-5.

The beryl-spodumene zone (3) of trench SA-1 is characterized by very coarse-grained green beryl crystals (up to 46 by 34 cm) together with white coarse-grained albite, quartz and green muscovite. A cluster of 10 coarse-grained green beryl crystals (> 2 cm) occur at the east end of the trench.

Trench SA-3 consists of alternating layers (up to 4 m thick) of albite-spodumene layers and plumose muscovite layers. The albite-spodumene layers (4) contain coarse-grained spodumene, white albite, quartz and beryl. The green spodumene is very coarse-grained and attains lengths up to 56 cm by 6 cm thick. Beryl only occurs in the albite-spodumene layers and it shows 2 types of zoning: a) pink rims and white cores and b) green rims and grey cores. The albite-spodumene layers also contain minor blue fluorapatite and radiating blades of tantalum-oxide minerals.

MINERAL CHEMISTRY

The following is a summary of the results of the study on the mineral chemistry of the tantalum-oxide minerals by Breaks, Selway and Tindle (2001, and in press). The most common tantalum-oxide minerals at the North Aubry pegmatite are manganocolumbite and manganotantalite (Figure 6.4a). Increasing tantalum content in columbite-tantalite is due to increasing fractionation of the pegmatite melt. The tantalum content in the oxide minerals increases from 1) the aplite pods (average 42 weight % Ta_2O_5) and outer sodic zone (average 51 weight % Ta_2O_5) with mostly manganocolumbite and minor manganotantalite; to 2) aplite dike (average 51 weight % Ta_2O_5), quartz-plagioclase border zone (42 to 62 weight % Ta_2O_5) and spodumene main zone (36 to 67 weight % Ta_2O_5 for 135 compositions) with a range from manganocolumbite to manganotantalite; to 3) almost end-member manganotantalite (77 to 86 weight % Ta_2O_5 for 170 compositions) in the fractionated inner core zone. The inner core zone manganotantalite is the most tantalum-rich tantalite in Ontario.

In addition to manganocolumbite and manganotantalite, the North Aubry pegmatite also contains ferrotapiolite ($FeTa_2O_6$) and microlite [$Ca_2Ta_2O_6(O,OH,F)$]. Ferrotapiolite occurs only in the inner core zone as rims on or along fractures in the manganotantalite. Microlite occurs near the contact between the pegmatite and the host rock; in miarolitic cavities; in a 2 m thick aplite dike in trench NA-4; and in the outer sodic zone. Microlite occurs as a replacement of manganotantalite and ferrotapiolite.

Rare very fine-grained uranmicrolite occurs in the outer sodic zone, which is 4 cm from the biotite-rich host rock. The uranmicrolite is mantled by magnetite and contains up to 5.7 weight % UO_2, 2.4 weight % Sc_2O_3 and 66.7 weight % Ta_2O_5.

The tantalum-oxide minerals in the South Aubry trench SA-3 are more tantalum-rich than those in North Aubry trenches NA-1 to NA-4 (Figure 6.4b). Platy black manganotantalite (average 68 weight % Ta_2O_5) mainly occurs as radiating aggregates up to 1 to 6 mm by 2 cm in size and occur locally in the spodumene layers. A late veinlet of tantalum-poor manganotantalite (average 55 weight % Ta_2O_5) cuts the largest manganotantalite grain that was examined. Small euhedral uranoan microlite occurs in the beryl-spodumene zone of trench SA-1.

There are many similarities between beryl compositions from the North and South Aubry spodumene-subtype pegmatites and the petalite-subtype Tanco pegmatite mine, southeastern Manitoba (Figure 6.5a). Most notable is the division between low- and high-cesium beryl (averaging 0.51 and 2.78 weight % Cs_2O at Tanco). In the North Aubry pegmatite, in the potassium feldspar zone (one of the intermediate zones), this bimodality is marked by average compositions of 0.38 and 2.47 weight % Cs_2O. The main cause for this variation seems to be the passage of late-magmatic (cesium-rich) fluids through the already crystallized parts of the pegmatite, which were able to partially recrystallize early formed beryl. In later zones of the pegmatite (such as the North Aubry inner core zone), only high-cesium beryl is found (average 2.83 weight % Cs_2O), and none with replacement textures. A likely model is that fluids from the most evolved part of the pegmatite escaped into the earlier crystallized zones, partially replacing the beryl in these zones in the process.

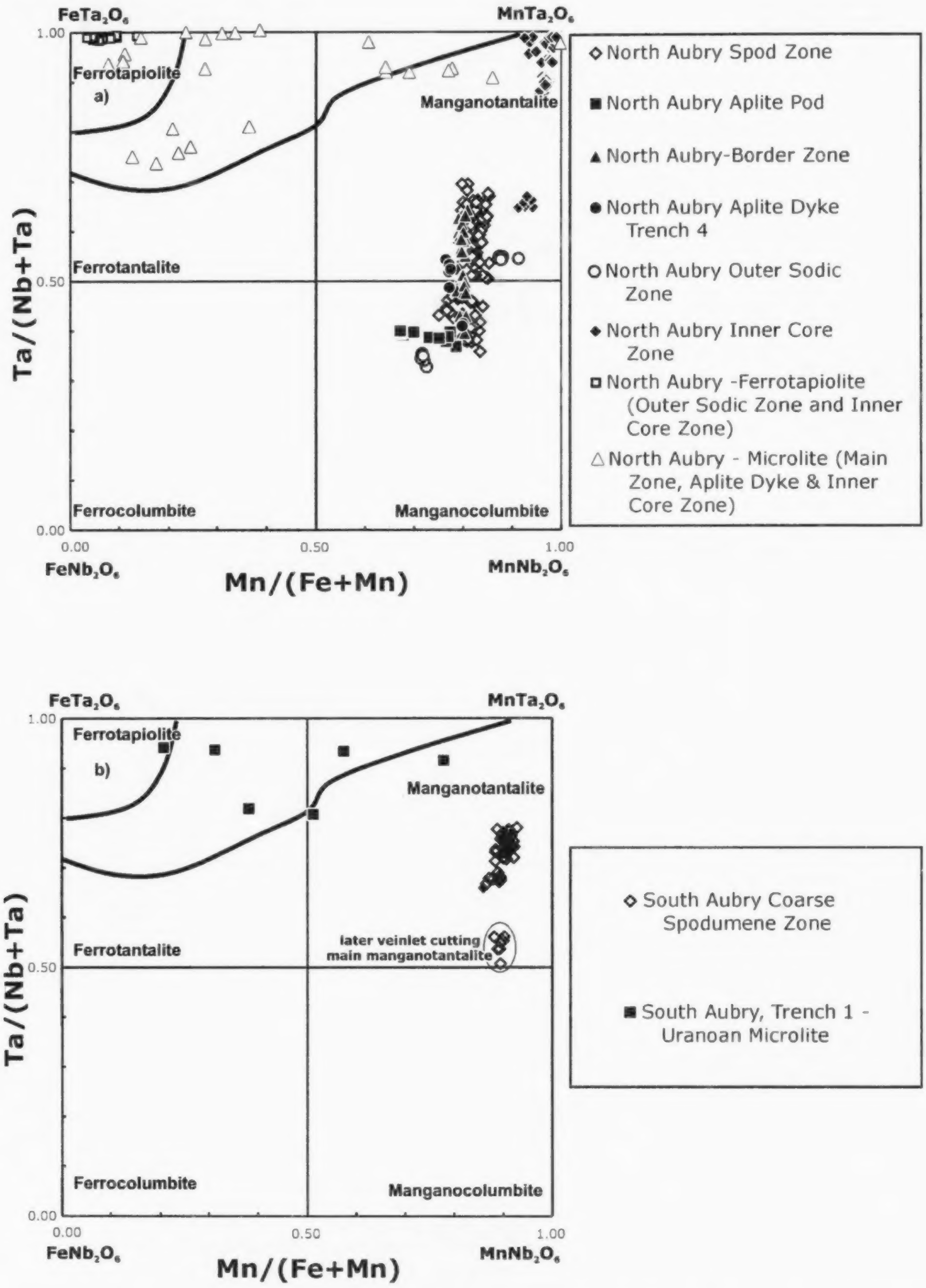

Figure 6.4. Columbite-tantalite quadrilateral plot for **a)** North Aubry pegmatite and **b)** South Aubry pegmatite. Compositional gap between ferrotapiolite and ferrotantalite is based on 5200 compositions of columbite-tantalite and tapiolite from Ontario. Microlite compositions may plot within this compositional space.

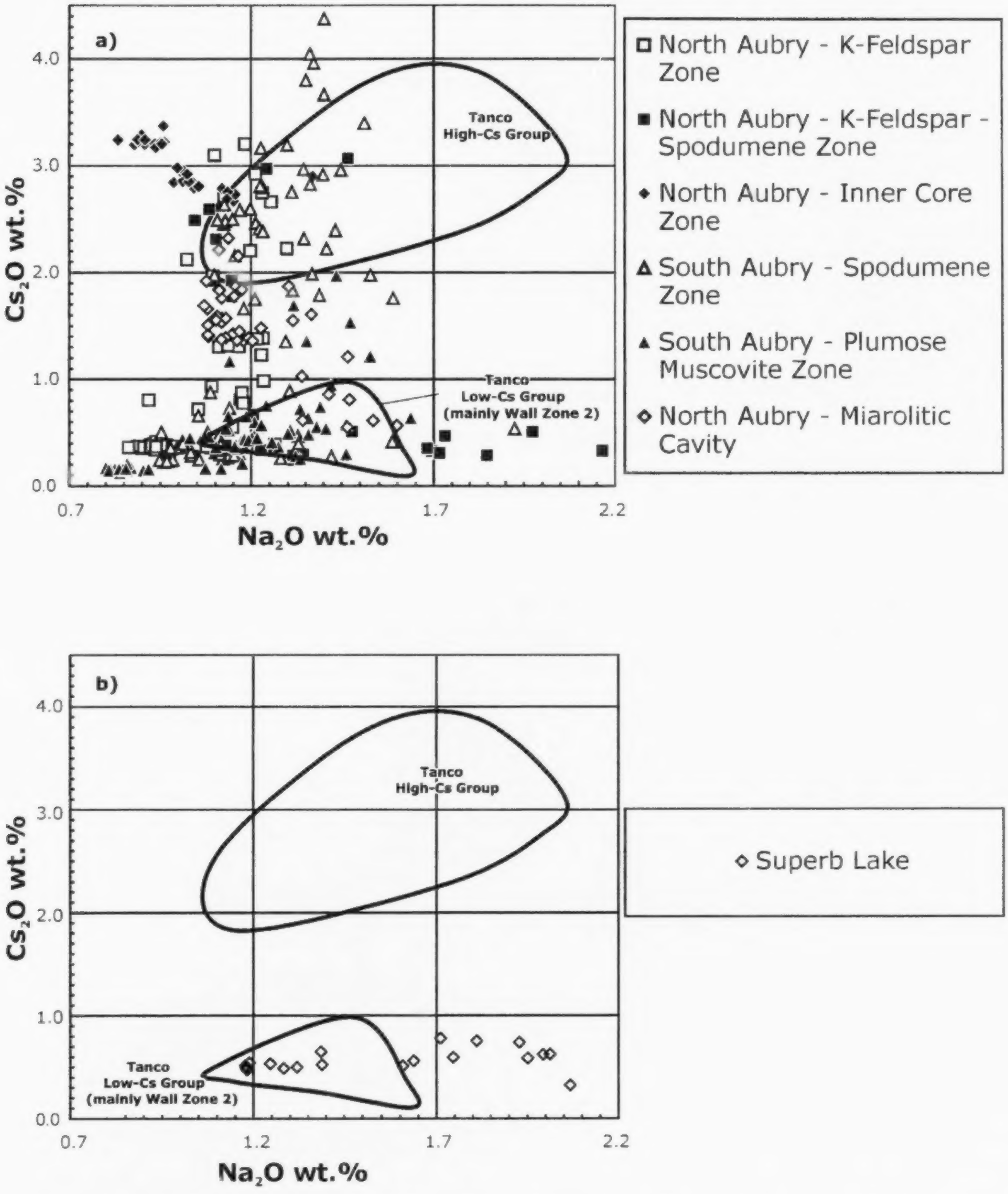

Figure 6.5. Cs_2O versus Na_2O weight % plot for beryl compositions from **a)** North and South Aubry pegmatites and **b)** Superb Lake pegmatite. Circled areas represent the range in beryl compositions that occurs in the Tanco pegmatite.

The South Aubry pegmatite contains beryl that has a complete solid solution from cesium poor to cesium rich and does not have the distinct compositional bimodality that is seen in beryl in the North Aubry pegmatite. Primary cesium-poor beryl is being replaced by cesium-rich beryl to produce extreme patchy zonation patterns. Similar patterns have been observed previously in columbite-tantalite minerals in North Aubry trenches NA-1 and NA-3 due to varied tantalum content. This patchy zoning in the beryl and columbite-tantalite indicates that the late evolving pegmatite-forming melt was both cesium and tantalum rich.

The presence of manganotantalite with elevated tantalum contents (77 to 86 weight % Ta_2O_5) and cesium-rich beryl (average 2.83 weight % Cs_2O) in the inner core zone of the North Aubry pegmatite indicates that this is the most fractionated zone in the pegmatite. During crystallization of a pegmatite melt, fractionation concentrates rare elements (e.g., lithium, rubidium, cesium, niobium, tantalum) in the late-stage fluids, which crystallize to form the innermost and final pegmatite zone. The economic minerals within a pegmatite are usually the last to crystallize. Oxide minerals with high tantalum contents are economic if the oxide grains are relatively abundant over a large area. Cesium-rich beryl indicates high cesium contents in the original pegmatite melt and may indicate the presence of pollucite. Pollucite is a cesium-aluminosilicate mineral, which is mined from the Tanco pegmatite to produce cesium formate used as a filler in oil drilling.

SOUTH AUBRY LEPIDOLITE BOULDER

The South Aubry lepidolite boulder (labelled SA-4 by Linear Resources Inc., UTM: 396795E, 5584287N, Zone 16) is located approximately 200 m south of the South Aubry pegmatite. The mineralogy of this lepidolite boulder indicates that it was not derived from the pegmatites in the area (i.e., North Aubry, South Aubry and Swole pegmatites). In hand sample, the boulder consists of dominant purple mica with common fresh grey spodumene, quartz and aplite patches and minor spodumene with green alteration. A detailed microprobe examination of samples from this boulder revealed the presence of wodginite, pollucite and montebrasite all of which are not found in pegmatites in the area.

The tantalum-oxide minerals in the lepidolite boulder consists of: manganotantalite, wodginite [$Mn(Sn,Ta)Ta_2O_8$] and uranium-rich microlite [$(Ca, U)_2Ta_2O_6(OH,F)$]. The manganotantalite contains elevated tantalum contents similar to that found in North Aubry trench NA-5 and the Central Intermediate Zone (6) of the Tanco pegmatite mine, southeastern Manitoba. The manganotantalite grains are typically less than 50 μm in length and relatively uncommon with an average of 81.2 weight % Ta_2O_5. The wodginite occurs as 40 μm grains associated with the manganotantalite and has an average of 69.3 weight % Ta_2O_5. The presence of wodginite in this boulder is significant, as wodginite is the main tantalum ore mineral in the Tanco pegmatite mine. The uranium-rich microlite contains an average of 72.6 weight % Ta_2O_5 and 6.6 weight % UO_2.

The lithium minerals in the lepidolite boulder are abundant spodumene, montebrasite [$LiAl(PO_4)(OH,F)$] and minor lepidolite. In hand sample, lepidolite appears to be abundant, but actually most of the mica is muscovite partially replaced by lepidolite rims. The lepidolite rims have elevated rubidum and cesium contents (average 4.3 weight % Rb_2O, 0.82 weight % Cs_2O) relative to the muscovite cores (average 2.7 weight % Rb_2O, 0.36 weight % Cs_2O). Fluorapatite is a minor phosphate mineral with high fluorine contents and moderate manganese contents.

In addition to micas with elevated cesium contents, pollucite [$(Cs,Na)AlSi_2O_6 \cdot nH_2O$] and cesium-rich beryl also occur in the lepidolite boulder. Pollucite occurs as infill to cleavage and fracture surfaces within earlier crystallized spodumene. The presence of pollucite is significant because it indicates an extremely high degree of fractionation and it is the cesium ore mineral in the Tanco pegmatite mine. One euhedral grain of beryl (310 μm across) was found in the samples analyzed. The beryl is zoned with "filaments" with elevated cesium. The overall average cesium content in the beryl is 3.2 weight % Cs_2O with the highest values occurring in the rim.

The angular nature of this boulder and the fact that its mineral assemblage is different from the Aubry pegmatites indicate that it is derived from another pegmatite nearby. It is recommended that the area around the South Aubry lepidolite boulder be searched to find the pegmatite from which it was derived. The presence of tantalum-rich manganotantalite, wodginite and microlite and cesium-rich pollucite and beryl in this boulder indicates that it is derived from a highly fractionated pegmatite.

Swole Lake Pegmatite

This rare-element occurrence represents a new discovery by prospectors M. and S. Stares of Thunder Bay in 2001. The locality comprises a 60 by 100 m boulder field, near the western shoreline of Swole Lake (*see* Figure 6.2), in which a high percentage of the angular boulders are composed of lepidolite-spodumene pegmatite. The pegmatite boulders are characterized by abundant lepidolite, altered spodumene mantled by lepidolite and albitized potassium feldspar.

The pegmatite boulder at locality 02-JBS-18 (UTM: 433157E, 5588229N, Zone 16) is 0.9 m long by 2.1 m wide with a minimum depth of 0.7 m. The host rock is a fine-grained, foliated, metasedimentary rock with 1 to 2 volume % quartz circular phenocrysts (up to 3 mm in size). The pegmatite contains abundant altered spodumene, lepidolite, cleavelandite, pink blocky albitized potassium feldspar, quartz, minor blades of manganotantalite (10 by 1 mm) and rare blue fluorapatite. The fresh spodumene is faint green to pale pink and white and is oriented perpendicular to the contact with the host rocks (comb texture). The spodumene is altered, pseudomorphed and mantled by fine-grained lepidolite (lithium-rich mica). Most of the lepidolite appears to be secondary in origin. Spodumene is also altered to dark green chlorite and red hematite.

The pegmatite boulder at locality 02-JBS-19 (UTM: 433155E, 5586193N, Zone 16) is 2 m long by 2.5 m wide with a minimum depth of 1.5 m. A thin section from a sample of the metasedimentary host rock, collected 40 cm from the contact with the pegmatite, contains fine-grained quartz, coarse-grained hornblende, sericitized feldspar and minor epidote and chlorite. The host rock contains a layer of biotite, quartz and chlorite and is intruded by quartz veins. A thin section of the host rock–pegmatite contact indicates that the host rock is rich in biotite along the contact. The pegmatite at the contact contains strongly sericitized feldspar with quartz inclusions, whereas the pegmatite 4 mm from the contact contains unaltered albite, quartz and muscovite. This indicates that at the host rock–pegmatite contact, potassium-rich metasomatic fluids from the pegmatite melt formed a biotite-rich aureole within the host rock and altered the feldspar to sericite within the pegmatite. In outcrop, the pegmatite has a 1 cm thick aplite border zone, and the main pegmatite zone is the same as that at 02-JBS-18 with the addition of minor purple fluorite. The fact that boulders 02-JBS-18 and 02-JBS-19 have the same mineral assemblage indicates that they came from the same pegmatite.

The pegmatite boulder at locality 02-JBS-22 (UTM: 433170E, 5586171N, Zone 16) contains a 75 cm wide holmquistite zone in a quartz-feldspar porphyry in contact with pegmatite. Holmquistite is a lithium-amphibole, which only occurs in metasomatized host rocks next to lithium-rich pegmatites. Holmquistite is used as an exploration tool in search of unexposed rare-element pegmatites. The pegmatite contains coarse cleavelandite, quartz and an unknown cubic brown mineral.

It is hypothesized that the abundance of large, angular, rare-element-mineralized boulders represent frost heaving from the actual buried pegmatite at subsurface. Hence, attention to boulder prospecting in the general area is recommended, as similar such accumulations of pegmatite boulders may be present.

MINERAL CHEMISTRY

The following discussion of the composition of the oxide minerals in the Swole Lake boulders is preliminary, as it is based on only 1 sample. More electron microprobe work on this locality will be completed in the fall of 2002. The composition of the columbite-tantalite from this sample is unique in Ontario pegmatites mainly because of an exceptionally low iron content, which results in the data plotting along the right-hand margin of the columbite-tantalite quadrilateral (Figure 6.6). This is a characteristic of lepidolite-subtype pegmatites, which frequently have Mn/(Mn+Fe) ratios greater than 0.9. The manganotantalite also contains a high tantalum content, which, on the basis of 68 analyses, has an average of 68.9 weight % Ta_2O_5 (range 53.2 to 84.5 weight %).

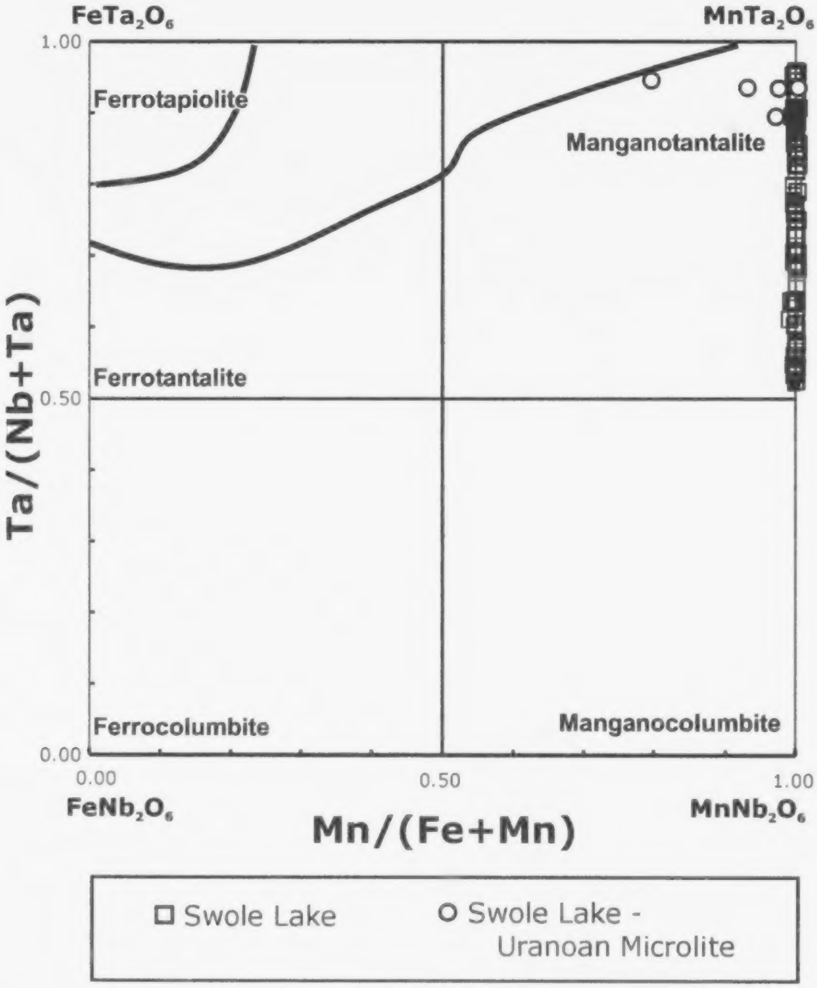

Figure 6.6. Columbite-tantalite quadrilateral plot for Swole Lake pegmatite boulders. Compositional gap between ferrotapiolite and ferrotantalite is based on 5200 compositions of columbite-tantalite and tapiolite from Ontario.

The manganotantalite forms euhedral, rectangular crystals up to 1 mm in length and are characterized by concentric zonation. Some of this zonation is oscillatory, but the dominant trend is from a tantalum-poor core to a tantalum-rich rim. Some grains have radial fractures likely of metamict origin due to a small, but significant, uranium content, averaging at 0.07 weight % UO_2 (but reaching a maximum of 1.29 weight % in the core of one grain). Many analyses have uranium below the probe detection limit, which is estimated to be 0.02 weight % UO_2.

There is some evidence that late replacement of manganotantalite by secondary microlite has occurred, as a number of manganotantalite analyses show a small calcium content (the first step in the alteration process before replacement takes place). It was not possible to generate data from most of the microlite grains, due to its limited extent, degree of alteration and intergrowth with manganotantalite. The presence of iron-free manganotantalite and microlite with elevated tantalum contents indicate that the oxide minerals crystallized from a fractionated pegmatite melt. Oxide minerals that are rich in tantalum may be economic, if they are relatively abundant and cover a large area.

Ketchican Road Beryl Occurrence

Pale green beryl was discovered in a pale pink, 2 m wide dike of garnet-biotite-muscovite pegmatitic leucogranite near the south side of the Ketchican Lake road (Locality 02-FWB-41: UTM: 411242E, 5586228N, Zone 16). The dike strikes about 010° with a steep undetermined dip to the west and is hosted in tonalitic rocks that comprise a large granitic terrane situated south of the Onaman–Tashota terrane (*see* Figure 6.2). The euhedral beryl crystals are mostly hosted within a 20 by 52 cm quartz-rich patch and have maximum dimensions of 2.3 by 2.7 cm and 3 by 5 cm, respectively, in sections normal and parallel to the *c*-axis. This is a new occurrence removed from the other pegmatite groups in the Seymour, Crescent and Falcon lakes area, therefore, further prospecting within the tonalite-trondhjemite-granodiorite terrane south of the Onaman–Tashota terrane is encouraged, as this beryl occurrence could be part of a larger zoned rare-element pegmatite sequence.

Rare-Element Dispersion in Mafic Metavolcanic Rocks, North Jackfish Road

Significant lithochemical dispersion was detected at locality 02-FWB-40 (UTM: 411173E 5588515N, Zone 16) on the North Jackfish Road. A 2 m wide, white weathering dike consisting of apatite-garnet-muscovite potassic pegmatite occurs within undeformed intermediate metavolcanic rocks. In the part of the outcrop, near the western side of the road, 2 samples were collected from mafic metavolcanic rocks about 20 m from the pegmatite dike. These samples are

02-FWB-40-04:	biotite-rich (80 volume %) highly metasomatized, mafic metavolcanic rocks adjacent to a 30 cm thick quartz vein. (UTM: 411173E 5588515N, Zone 16)
02-FWB-40-05:	mafic metavolcanic rock, with 5 volume % biotite porphyroblasts, collected about 3 m from 02-FWB-40-04. (UTM: 411173E 5588515N, Zone 16)

Analytical results from these samples, received from the Geoscience Laboratories at the time of writing, indicate the presence of highly anomalous levels of Rb (1485 ppm), Li (551 ppm), Cs (411 ppm), Sn (81 ppm), Ta (76 ppm) and Nb (30 ppm). Mafic metavolcanic rocks do not commonly contain such high levels of these elements (Taylor and McLennan 1985, p.181). The amount of tantalum obtained in sample 02-FWB-40-04 is the second highest value documented during this current project. Such an anomalous level has never been previously observed by the authors within host rocks that have been metasomatized by rare-element pegmatite systems in Ontario. Lower, but still anomalous, levels of Li (179 ppm), Rb (176 ppm) and Cs (44 ppm) were determined in sample 02-FWB-40-05. These analytical results suggest that an unexposed rare-element pegmatite system is located in the vicinity of these metasomatized mafic metavolcanic rocks. Therefore, more work is recommended in the area. The nearest known rare-element pegmatite swarm to this location is situated about 3.5 km to the northwest (Crescent Lake group: *see* Figure 6.2).

NAKINA AREA

This area was briefly examined due to the presence of the Superb Lake pegmatite, which has not had detailed mineralogical and chemical investigation (Figure 6.7). The most recent geological–structural investigation in the O'Sullivan Lake area was conducted by Stott and Parker (1997). A reconnaissance examination was also directed at peraluminous granitic rocks described by Stott and Parker (1997) and Parker and Stott (1998) in the Maytham–Queenston and Odman lakes areas.

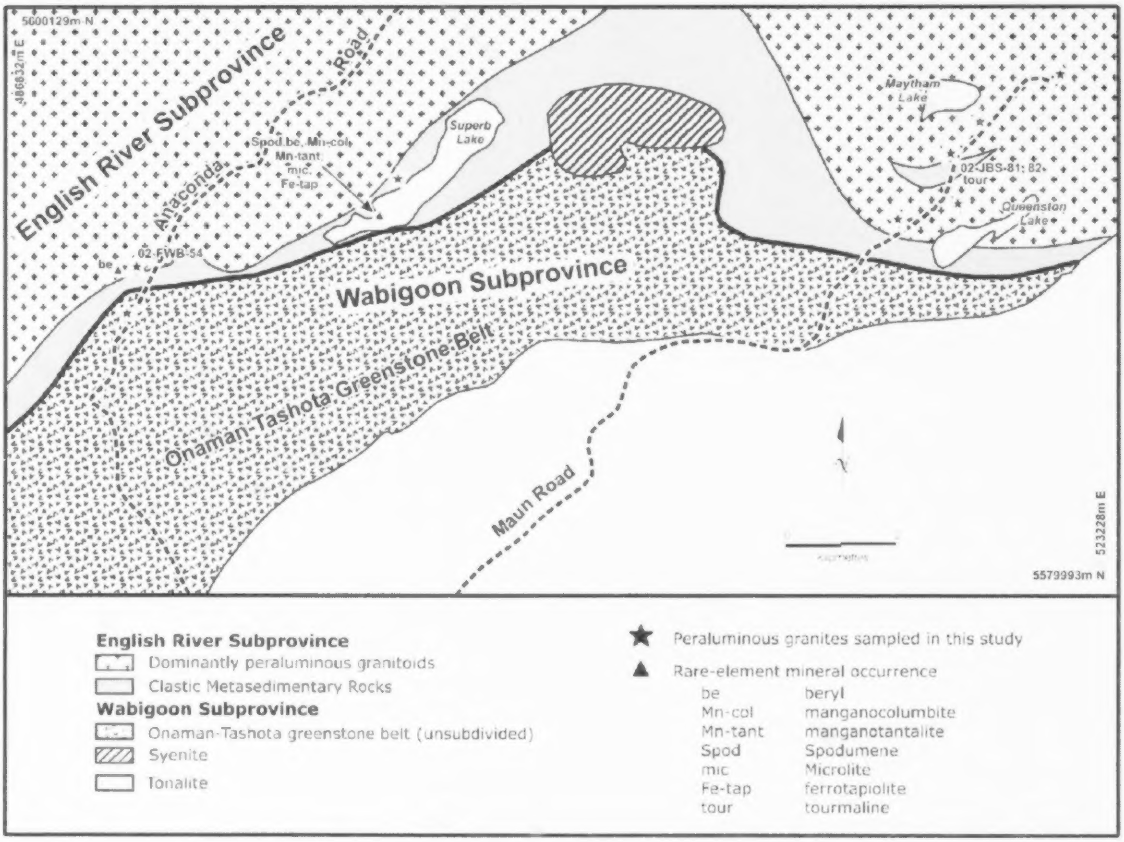
5600129m N
486832m E
English River Subprovince
Road
Anaconda
Spod.be, Mn-col,
Mn-tant,
mic,
Fe-tap
Superb Lake
02-FWB-54
be
Maytham Lake
02-JBS-81; 82
tour
Queenston Lake
Wabigoon Subprovince
Onaman-Tashota Greenstone Belt
Maun Road
523228m E
5579993m N
English River Subprovince
Dominantly peraluminous granitoids
Clastic Metasedimentary Rocks
Wabigoon Subprovince
Onaman-Tashota greenstone belt (unsubdivided)
Syenite
Tonalite
★ Peraluminous granites sampled in this study
▲ Rare-element mineral occurrence
be beryl
Mn-col manganocolumbite
Mn-tant manganotantalite
Spod Spodumene
mic Microlite
Fe-tap ferrotapiolite
tour tourmaline

Figure 6.7. General geological location of rare-element mineralization in the English River–Wabigoon subprovincial boundary zone, north of Nakina (geology *modified after* Stott and Parker 1997).

Peraluminous Pegmatitic Granitic Rocks

Potentially fertile rocks of this type were noted at the following localities (*see* Figure 6.7):

- Maun Lake Road near Maytham and Queenston lakes
- Abamasagi Lake Road in vicinity of its junction with the Anaconda Road
- northwestern shoreline of Superb Lake

MAYTHAM–QUEENSTON LAKES PEGMATITIC GRANITE

Stott and Parker (1997, p.50) documented a large mass of pegmatitic granite between these two lakes characterized by "abundant coarse muscovite, pink to lilac garnets and small enclaves of metasedimentary rock" (*see* Figure 6.7). This elliptical, 10 by 13 km mass of peraluminous, massive, undeformed granite lies in contact with metasedimentary rocks of the English River Subprovince (G.M. Stott, Ontario Geological Survey, personal communication, 2002). Several outcrops scattered across a 10 km area, roughly normal to the contact with metasedimentary rocks of English River Subprovince, were examined by the authors.

Locality 02-JBS-81 and 02-JBS-82 (UTM: 518782E, 5595264N, Zone 16) is a single large outcrop of white potassic pegmatite and aplite between Maytham and Queenston lakes. The potassic pegmatite displays several characteristics of a peraluminous fertile granite: radiating fans of green plumose muscovite + quartz intergrowths; graphic blocky potassium feldspar; local graphic tourmaline and garnet-green muscovite aplite layers. The potassic pegmatite also contains muscovite greater than biotite, minor red garnet and blue apatite. In general, fertile granites represent the sources or parent magmas to nearby rare-element pegmatites.

At locality 02-FWB-56 (UTM: 519552E 5595927N, Zone 16), garnet-muscovite potassic pegmatite is layered with minor garnet-muscovite granite. Orientation of layering is 060/50° south. Silver muscovite books, up to 2 by 20 cm, are abundant whereas black tourmaline is sparse. Blocky potassium feldspar, up to 20 by 40 cm, is scattered throughout the main potassic pegmatite unit. Quartz-muscovite intergrowths, as radiating and blob-like entities up to 15 by 100 cm, represent a conspicuous feature and is similar to other fertile granites examined by the authors, as near Onion Lake and at the South Aubry spodumene pegmatite (Breaks, Selway and Tindle 2001).

Further to the east, at locality 02-FWB-57 (UTM: 524118E, 5597656N, Zone 16), the mineral assemblage within the pegmatitic granite changes with a decrease in the abundance of muscovite and disappearance of tourmaline into a muscovite-garnet-biotite potassic pegmatite containing narrow layers of garnet-biotite aplite.

Abamasagi Road Pegmatitic Granite

A well-exposed, glacially polished outcrop of garnet-biotite-muscovite pegmatitic leucogranite was observed at locality 02-FWB-54 along the Abamasagi Lake road near the junction with the Anaconda Road (UTM: 490691E, 5591192N, Zone 16) (*see* Figure 6.7). Fertile peraluminous granite intrusions exposed at this locality contain

- pegmatitic leucogranite
- sodic aplite layers
- quartz-rich patches with blocky potassium feldspar and sparse green beryl
- potassic pegmatite segregations

The main intrusive phase is a garnet-biotite-muscovite pegmatitic leucogranite with abundant plumose intergrowths of quartz + muscovite which is quite reminiscent of phases in the South Aubry pegmatite. This pegmatitic leucogranite unit is conspicuous due to the presence of many bright pink megacrysts of graphic quartz-potassium feldspar intergrowths that are up to 20 by 32 cm in size (Photo 6.2a). These megacrysts are embedded within a white matrix that is mainly a graphic intergrowth of quartz and albite. Graphic intergrowths of coarse-grained muscovite and quartz are interstitial to the albite crystals.

The pegmatitic leucogranite locally is gradational into very coarse patches that are quartz rich with blocky potassium feldspar crystals up to 40 cm in diameter. Irregular masses of potassic pegmatite also occur along the periphery of the quartz patches and comprise an irregular aggregate of blocky potassium feldspars. One of the quartz-rich patches contains sparse, faint green, beryl crystals up to 0.8 cm in diameter and 3 cm parallel to the length of the crystal (Photo 6.2b). Garnets are found locally in the quartz-rich patches and reach up to 1.5 by 2 cm in size.

Sparse green, sugary aplite are interlayered with an albite-rich, coarser grained, 5 to 10 cm thick unit garnet-biotite-quartz-albite that locally contains bright pink, blocky, potassium feldspar crystals.

Northwest Shoreline Of Superb Lake

An exposure of sheared pegmatitic granite, which represents a dike at least 30 m in width, is exposed at 02-JBS-63 (UTM: 499104E, 5592820N, Zone 16) (*see* Figure 6.7). The main unit comprises garnet-muscovite potassic pegmatite accompanied by approximately 30% garnet-muscovite aplite. Most of the shearing is focussed in the aplite unit. This dike, previously mapped by Parker and Stott (1998), is hosted by metasedimentary rocks of the English River Subprovince.

SUPERB LAKE PEGMATITE

This lithium-rich pegmatite (*see* Figure 6.7) occurs within medium-grade, metasedimentary rocks of the English River Subprovince directly adjacent to its boundary with the Onaman–Tashota terrane in the O'Sullivan Lake area. The pegmatite was apparently discovered around 1955 by unspecified individuals (Mulligan 1965, p.63) and evidence of work possibly from that date was noted in an old blast pit. A large bulk sample, collected from the pegmatite by G.M. Stott from the blast pit area (G.M. Stott, Ontario Geological Survey, unpublished data, 1998), analyzed greater than 350 ppm Ta, 142 ppm Be, 80 ppm Nb, 1464 ppm Rb, 99 ppm Cs and 56 ppm Sn.

The work undertaken in this project included thorough washing of the pegmatite surface prior to mineralogical and bulk rock sampling.

The pegmatite has a minimum exposed strike length of 16 m and its width varies from 2.5 m at the shoreline to a maximum of 3.7 m where an old blast pit was excavated. Most of the blasted material appears to have been removed or blasted into the lake. The contact between the pegmatite and well-foliated, biotite, metawacke and metapelite host rocks is only exposed along the south contact between the lake and the blast pit.

The pegmatite exhibits deformation by internal thin shears that are locally anastomosing and by several re-entrants of metasedimentary host rock into the pegmatite along the southern contact. The contact is not planar as would be the case in a posttectonic emplaced pegmatite, such as the Tot Lake pegmatite in the Dryden area (Breaks and Janes 1991).

Several narrow pegmatite veins are situated within 30 m of the main pegmatite and reveal important evidence for the style of deformation. These pegmatites are deformed to different degrees and one dike, situated 12 m south of the Superb pegmatite, has been dismembered and deformed into a train of Zshaped, rotated boudins (Photo 6.3). These dikes are definitely part of the same rare-element-mineralization event as indicated by presence of white beryl and numerous specks of black oxide minerals. Several rusty patches may indicate the presence of uranmicrolite.

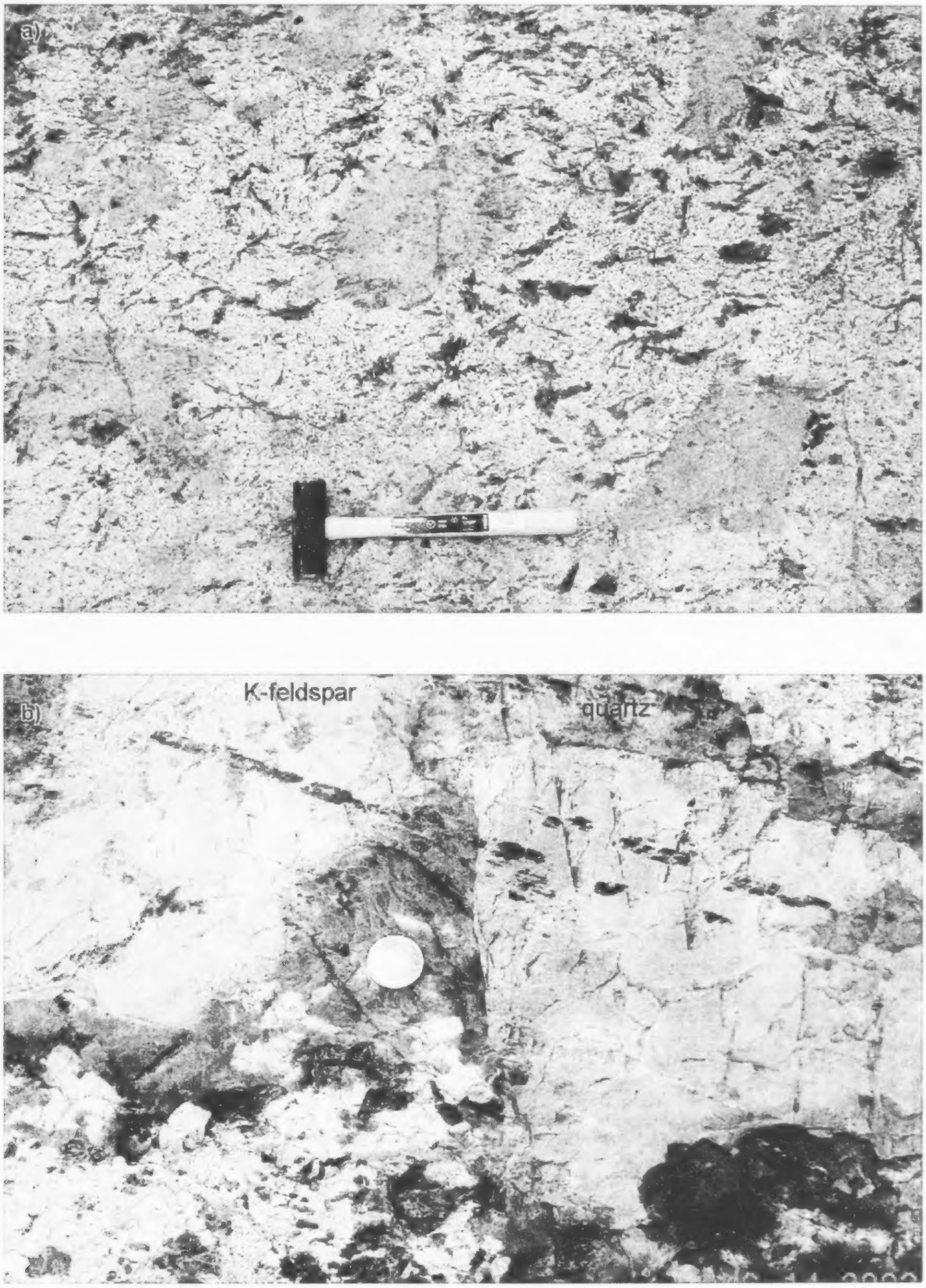

Photo 6.2. Abamasagi Lake road. **a)** Pegmatitic leucogranite with pink potassium feldspar megacrysts in a white matrix of graphic albite + quartz and graphic coarse-grained muscovite + quartz. **b)** Pegmatitic leucogranite with pink potassium feldspar megacrysts and interstitial quartz patches with minor green beryl. The beryl crystal is below and to the left of the two dollar coin.

The varied orientation of the pegmatite contact is due to deformation as is evidenced from the varied measurements: 260/58N; 247/50N; 030/32N; and 090/82N. The contact appears particularly warped adjacent to a local zone of intense phosphate-mica alteration of the metasedimentary host rock. Metasomatism of the host rocks is generally insignificant except for a 50 by 110 cm area of intense mica-rich alteration that consists of biotite porphyroblasts, fine-grained yellow-green sericite and local concentrations of blue-green apatite.

Vague internal zonation involves a central, coarser grained unit of muscovite-potassium feldspar-spodumene-quartz assemblage that is 50 to 70 cm wide and 6 m in strike length and that is gradational outward into an intermediate zone of fine-grained muscovite-quartz-spodumene-albite pegmatite. The core zone contains the coarsest spodumene crystals that may be up to 4 by 35 cm in sections parallel to the long axis. Otherwise, the grey to pale green spodumene crystals are typically randomly oriented. A significant number of spodumene crystals are partially to completely altered to aphanitic, yellow green and dark green black secondary minerals.

Along southern margin of the spodumene-quartz-rich core unit is a finer grained assemblage of quartz-spodumene-sericite-albite. This zone is characterized by 30% fine-grained masses that are rich in yellow-green sericite. It is plausible that the yellow-green masses represent altered spodumene, however, no relict cores of unaltered spodumene were identified. Alternatively, the sericite masses may represent concentrations of potassium that were released during albitization of potassium feldspar. The potassium may have been redistributed during shearing deformation, which obviously affects this part of the pegmatite. The wall zone of the pegmatite consists of a 50 cm wide assemblage of muscovite-quartz-albite. Transverse quartz veins, 10 to 35 cm in width and up to 1.9 m in length, are oriented normal to the dike contact. These veins are devoid of other pegmatite mineral phases.

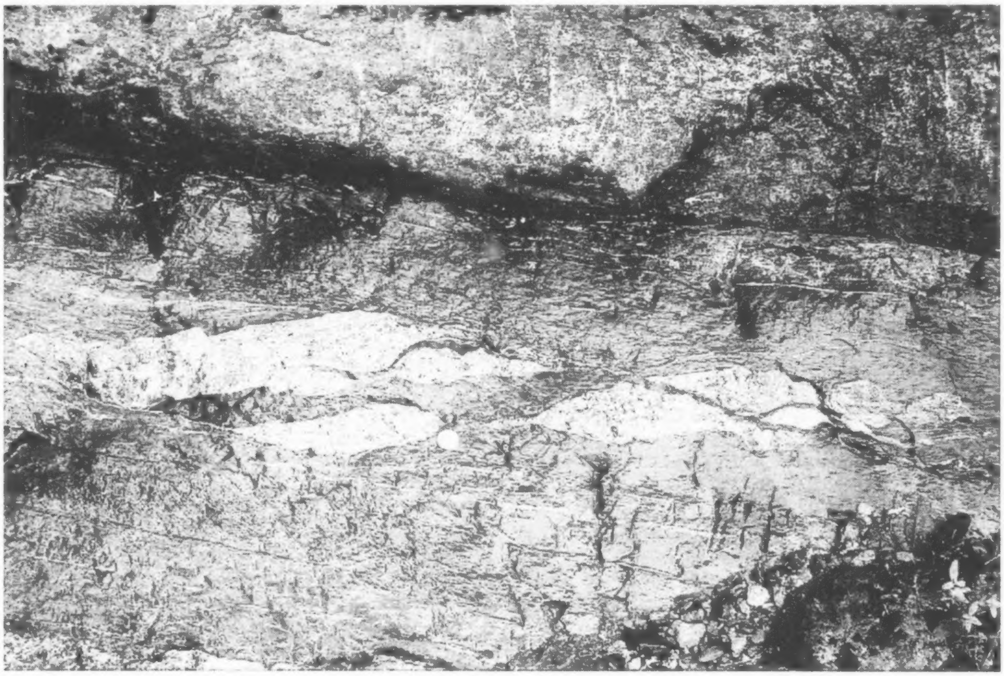

Photo 6.3. Rare-element-enriched felsic rotated boudins in metasedimentary rocks next to the Superb Lake pegmatite.

Mineral Chemistry

Four samples, collected by G.M. Stott, from the Superb Lake pegmatite were examined by an electron microprobe. The columbite-tantalite is characterized by minor to strong oscillatory zonation and forms prismatic laths in which the overall change in composition is from tantalum-poor to tantalum-rich end-members. Columbite-tantalite compositions vary considerably amongst the samples, therefore, the results from each sample are summarized separately (Figure 6.8):

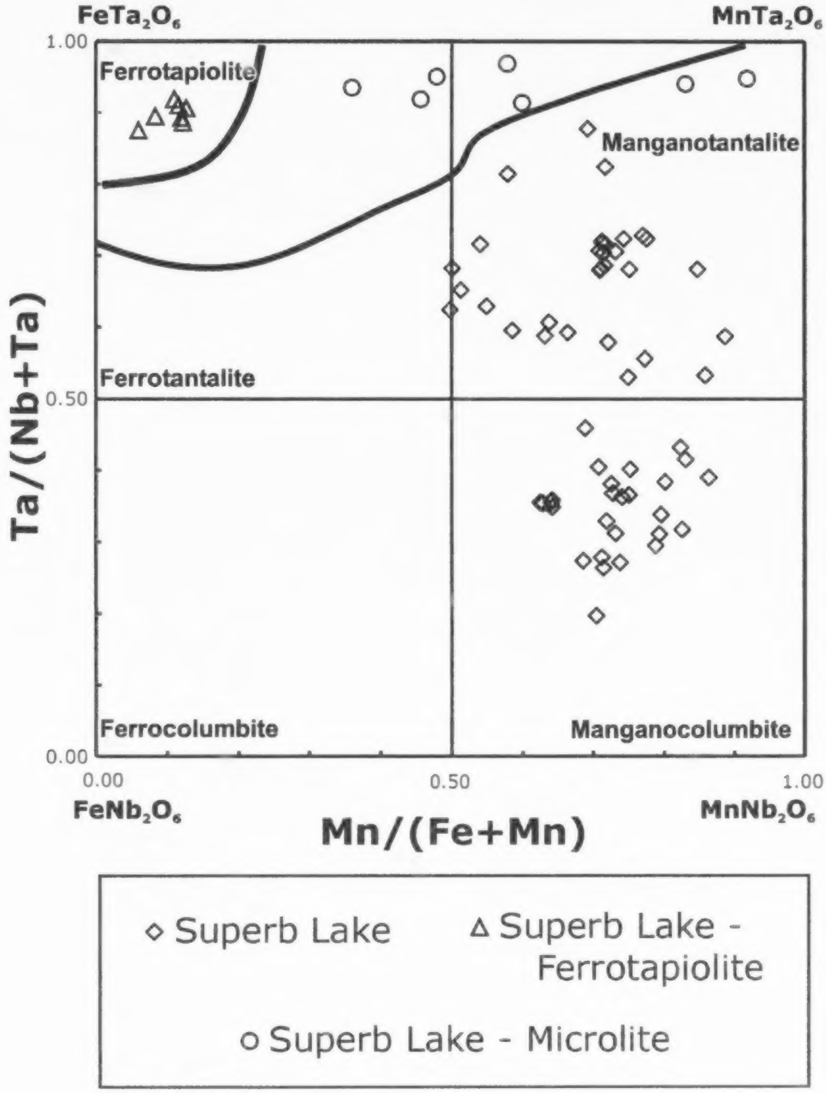

Figure 6.8. Columbite-tantalite quadrilateral plot for Superb Lake pegmatite. Compositional gap between ferrotapiolite and ferrotantalite is based on 5200 compositions of columbite-tantalite and tapiolite from Ontario. Microlite compositions may plot within this compositional space.

- The oxide minerals in sample 97GRS215 are mostly manganocolumbite (average Ta_2O_5 = 38.3 weight %, range from 23.3 to 54.2 weight % for 18 analyses) with minor oscillatory zonation.
- The oxide minerals in sample 97GRS215C are mostly manganotantalite (average Ta_2O_5 = 62.8 weight %, range from 35.8 to 69.2 weight % for 24 analyses) with strong oscillatory zonation. The columbite-tantalite is also notable for containing inclusion-rich zones.
- The oxide minerals in sample 97GRS215D are mostly manganotantalite (average Ta_2O_5 = 62.4 weight %, range from 53.9 to 73.8 weight % for 11 analyses) with strong oscillatory zonation. This average excludes one grain of manganocolumbite (possibly a relict from an earlier phase of crystallization) found amongst the manganotantalite. This sample also contains mottled patches of microlite that could not be satisfactorily analyzed.
- Sample 97GRS215A is different from the others as it contains ferrotapiolite as the main primary tantalum-oxide minerals. It forms anhedral patchy grains with irregular margins that have been partially resorbed and replaced with microlite. Some microlite is euhedral, indicating that crystallization of the pegmatite began in the ferrotapiolite stability field, but ended in the microlite field. Both minerals contain exceptionally high Ta_2O_5 contents: ferrotapiolite has an average 79.3 weight % Ta_2O_5 from 7 analyses and microlite has an average of 77.2 weight % Ta_2O_5 from 7 analyses.

Unlike microlite from other pegmatites (such as the Swole pegmatite), microlite in the Superb Lake pegmatite contains low amounts of radioactive elements.

Exploration Recommendations

The brief work undertaken by this project in the O'Sullivan Lake area has revealed an interesting assortment of potentially fertile, peraluminous pegmatitic granites (Maytham–Queenston lakes, near Odman Lake and on Superb Lake), coupled with a known, lithium-rich, rare-element pegmatite occurrence. The Maytham–Queenston pluton, in particular, resembles fertile pegmatitic granites observed by the authors in the Allison Lake batholith and in the Onion Lake area (Breaks, Selway and Tindle 2001). During this project, a new rare-element mineral discovery (UTM: 490691E, 5591192N, Zone 16) was made in beryl that was found in outcrops on the Abamasagi Lake Road and indicates that the pegmatitic granites in that area are at least locally fertile. Hence, the Superb–Odman–Abamasagi lakes area, in vicinity of the Wabigoon–English River subprovincial boundary, should be prospected for further rare-element mineralization.

QUETICO SUBPROVINCE

Reconnaissance evaluation of potentially fertile, peraluminous pegmatitic granitic rocks was undertaken in a 1000 km^2 area in the vicinity of the Town of Hearst. This area was studied due to the presence of a highly evolved rare-element pegmatite (complex-type, lepidolite- to spodumene-subtype based on the pegmatite classification system by Černý (1991)) in Lowther Township. This pegmatite is unique because it is hosted by its fertile, pegmatitic granite, parent, pluton (Breaks, Selway and Tindle 2001). This occurrence is situated within the central part of the Quetico Subprovince, similar to rare-element localities examined previously (Breaks, Selway and Tindle 2001) at Wisa Lake and in the Georgia Lake area (Pye 1965). Work at Hearst was also deemed important because a geochemical and/or mineralogical database relevant for rare-element deposits does not exist for this area.

General Geology

Most of the Hearst area was examined during reconnaissance geological mapping in the late 1960s (Bennett et al. 1966a, 1966b, 1967a, 1967b) as part of Operation Kapuskasing (Berger 1986). Detailed mapping in the area has only been undertaken by Berger (1985) and Berger, MacMillan and Roy (1986), who focussed upon metavolcanic belts that form part of the Quetico–Wawa subprovincial boundary zone. Between longitudes 84°00′ and 85°55′W, there is no record of any geological mapping in the Quetico Subprovince south of the boundary with the Wabigoon Subprovince along Highway 11. The area west of longitude 85°55′W along Highway 11 was mapped by Amukun (1983).

A generalized map of the Hearst area is presented in Figure 6.9. The main geological feature in this area is marked by 2 northeast-trending, *en échelon* masses of unsubdivided granitic rocks (Bennett et al. 1967a, 1967b) that approximately corresponds with the metamorphic transition from medium-grade, nonmigmatized metawacke and interbedded metapelites (in Shetland, Staunton, Orkney, Ebbs, Scholfield, Caithness and Rykert townships) to high-grade, layered migmatites in a large area to the northwest, between the towns of Hearst, Jogues and Lac St. Therese. The main rock type is metatexite that was mapped previously as "biotite-quartz-feldspar gneiss" by Bennett et al. (1967a, 1967b). This rock type has varied, foliation-concordant, white granitic to pegmatitic leucosome (5 to 20%) that has been invaded by later, generally pink, dikes and small masses of biotite-bearing, potassic pegmatite and fine- to medium-grained biotite granite.

PERALUMINOUS, PEGMATITIC GRANITES

Several scattered dikes and small masses, up to 30 by 100 m in size, of mineralogically more evolved granitic rocks were observed in unmigmatized metawacke of the Quetico Subprovince (*see* Figure 6.9):

- muscovite pegmatitic granite with minor biotite stock along Prune Creek road in Shetland Township (locality 02-JBS-17, UTM: 311622E, 5487250N, Zone 17)
- biotite-muscovite sodic pegmatite along Prune Creek road in Shetland Township (locality 02-JBS-16, UTM: 312061E, 5486226N, Zone 17)
- garnet-biotite-muscovite pegmatitic leucogranite mass near Coppell (location: UTM: 294295E 5488429N, Zone 17)
- aplite-pegmatite layered, muscovite pegmatite dike system with minor tourmaline exposed in quarry near Highway 11, east of Hearst, west of Montcalm Creek (locality 02-JBS-01 and 02, UTM: 358384E, 5489675N, Zone 17)
- muscovite potassic pegmatite dike cutting biotite granite on Highway 11, west of Hearst (locality 02-JBS-05, UTM: 298937E, 5509915N, Zone 17)
- muscovite potassic and sodic pegmatite with minor biotite in a 30 to 60 by 250 m mass that hosts the Lowther Township rare-element pegmatite (location: UTM: 302704E, 5485788N, Zone 17)
- garnet-biotite and muscovite < biotite pegmatitic leucogranite dikes in Pelletier Township that locally carry black tourmaline and was mapped by Berger (1985)(location: UTM: 618947E, 5512445N, Zone 17)

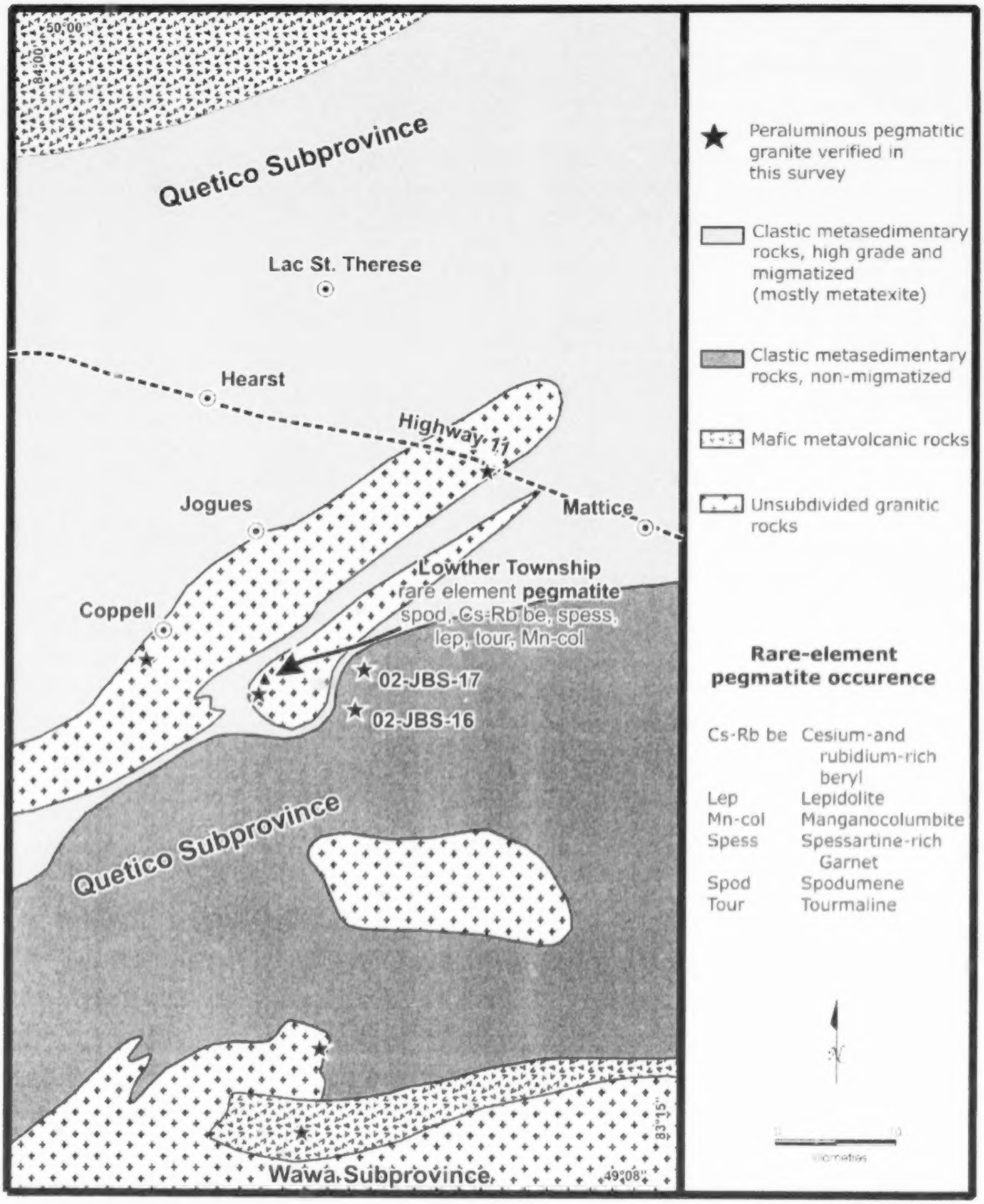
50°00'
84°00'
Quetico Subprovince
Lac St. Therese
Hearst
Highway 11
Jogues
Mattice
Coppell
Lowther Township
rare element pegmatite
spod, Cs-Rb be, spess,
lep, tour, Mn-col
02-JBS-17
02-JBS-16
Quetico Subprovince
Wawa Subprovince
83°15'
49°08'
★ Peraluminous pegmatitic granite verified in this survey
Clastic metasedimentary rocks, high grade and migmatized (mostly metatexite)
Clastic metasedimentary rocks, non-migmatized
Mafic metavolcanic rocks
Unsubdivided granitic rocks
Rare-element pegmatite occurence
Cs-Rb be Cesium-and rubidium-rich beryl
Lep Lepidolite
Mn-col Manganocolumbite
Spess Spessartine-rich Garnet
Spod Spodumene
Tour Tourmaline
N

Figure 6.9. General geological location of rare-element mineralization in the Hearst area, Quetico Subprovince.

New rare-element mineralization was detected at locality 02-JBS-16 by lithogeochemical sampling of a 3 m wide dike of biotite-muscovite sodic pegmatite. A large bulk sample of the dike, which also contains sparse apatite and garnet, analyzed anomalous levels of Rb (463 ppm), Be (98 ppm), Ta (78 ppm), Nb (60 ppm), Ga (29 ppm) and Sn (18 ppm). It also contains high Na_2O (8.63 weight %), and much lower K_2O (1.66 weight %) and CaO (0.24 weight %). A significant level of fractionation is revealed by a very low Nb/Ta (0.77), K/Rb (30), K/Ba (176) and Rb/Sr (24) ratios. This dike could have been derived from the large pegmatitic granite mass 1 km north at locality 02-JBS-17. Locality 02-JBS-17 consists of white muscovite potassic pegmatite with blocky potassium feldspar (up to 17 cm long) and coarse-grained muscovite (up to 6 cm across).

The quarry near Montcalm Creek on Highway 11, east of Hearst (localities 02-JBS-01 and 02-JBS-02), consists of 2 large pits. The quarry pit next to a pond consists of biotite granite with coarse-grained, graphic, pink, potassium feldspar (up to 26 cm long); quartz; bladed biotite and minor silver muscovite; fine-grained red garnet; and garnet that is altered to biotite. The mafic metavolcanic host rock is rich in biotite along the contact with the biotite granite. The quarry pit in the bush contains rocks more evolved than that in the pit next to the pond. The second pit consists of potassic pegmatite with a pod of coarse-grained pink potassium feldspar (up to 40 cm long) and quartz. The potassic pegmatite contains coarse-grained silver muscovite up to 9 cm across. The second pit also hosts a layered vein with a fine-grained green muscovite aplite layer, a coarse quartz core and a muscovite leucogranite layer. The muscovite aplite layer contains minor fine-grained red garnet, possible black tourmaline and rare green apatite. The muscovite leucogranite layer contains coarse-grained green muscovite, white potassium feldspar and minor garnet.

Locality 02-JBS-05, west of Hearst on Highway 11, consists of a fine-grained biotite granite intruded by a green muscovite potassic pegmatite (60 cm wide) dike. The dike is zoned with a fine-grained biotite muscovite granite outer zone, which gradually becomes a coarse-grained muscovite potassic pegmatite core zone. The potassic pegmatite core zone contains coarse-grained green muscovite (2 cm across by 2.5 cm thick) and white potassium feldspar altered to epidote, quartz and rare pyrite.

Potassic pegmatite dikes also intrude mafic metavolcanic rocks exposed on Prune Creek Road near the Quetico–Wawa subprovincial boundary (*see* Figure 6.9). Locality 02-JBS-14 consists of a muscovite potassic pegmatite dike (12 to 50 cm wide) in pillow metavolcanic rocks with calc-silicate pods. The pillows are flattened and lenticular and are metamorphosed to amphibolite facies. Biotite, tourmaline and garnet occur in pillow selvages. The potassic pegmatite dike contains abundant green muscovite, potassium feldspar, quartz and minor molybdenite and small miarolitic cavities (2 cm) lined with muscovite and quartz.

RARE-ELEMENT MINERALIZATION

Rare-metal mineralization in the Hearst area is restricted to the Lowther Township pegmatite (*see* Figure 6.9). It was discovered in 1939 by A. Villeneuve of Hearst when stripping and excavation of several shallow blast pits were undertaken (M.E. Hurst, Ontario Department of Mines, unpublished report, 1939). A later property examination was made by S.A Ferguson in 1955 when the property was owned by I. Topaloff of Hearst (S.A. Ferguson, Ontario Department of Mines, unpublished report, 1955).

Lowther Township Pegmatite

The Lowther Township rare-element pegmatite (*see* Figure 6.9) (UTM: 302704E, 5485788N, Zone 17) is at the metamorphic transition between medium- and high-grade metasedimentary rocks.

Emplacement of the pegmatitic granite parent mass is interpreted to have occurred after metamorphism as the pluton is undeformed and not recrystallized. The pegmatite occurs as a lens-shaped body, 3.7 to 11 m in width over a minimum length of 110 m, in which the long axis of the pegmatite is oriented at 110°. The pegmatite lens was previously explored by 4 blast pits situated in the middle 50 m of the pegmatite where it has the greatest width. The pegmatite is enclosed in a north-tapering mass of garnet-biotite pegmatitic granite that is locally enriched in sodium (4.81 weight % Na_2O) proximal to the Lowther Township pegmatite. There is a gradational contact between the Lowther Township pegmatite and its parent granite (potassic pegmatite). The white, coarsely graphic, parent granite contains blocky perthitic pink to white potassium feldspar, coarse-grained green muscovite (up to 5.5 cm across), and minor black tourmaline and garnet. The pegmatitic granite is enclosed within massive biotite-hornblende diorite.

The lepidolite- to spodumene-subtype Lowther Township pegmatite is sodic, as albite is more abundant than potassium feldspar. It is unknown which lithium mineral is dominant in the pegmatite—lepidolite or spodumene—although, the sodic nature of the pegmatite suggests that it is most likely a lepidolite-subtype pegmatite. Lepidolite-subtype pegmatites have albite more abundant than potassium feldspar in the innermost pegmatite zones, whereas spodumene-subtype pegmatites have potassium feldspar more abundant than albite (Selway et al. 1999; Breaks, Selway and Tindle 2002). The pegmatite is complexly zoned with 6 pegmatite zones from outermost part to the core:

1. sodic wall zone
2. aplite zone
3. spodumene zone (small exposure)
4. cleavelandite-rich zone with local coarse-grained beryl
5. lepidolite + cleavelandite pod (small exposure)
6. quartz core/pods with green muscovite and minor spessartine and black tourmaline

The above zonation is based on preliminary field observations. The sequence will be more accurately established using future microprobe analyses of mineral compositions.

The sodic wall zone of the pegmatite (1 m wide) consists of coarse pink to white cleavelandite, coarse-grained quartz, radiating green muscovite pods (~2 cm) with an unknown red-brown weathered mineral in the center, local fine-grained red garnet and minor graphic black tourmaline. The cleavelandite has orange staining and often shows iridescence indicating that the plagioclase (peristerite texture) is likely oligioclase in composition.

The aplite zone contains fine-grained cleavelandite and green muscovite. The aplite zone next to the spodumene zone contains approximately 1 cm miarolitic cavities and a 1 cm brown mineral with a radiation halo. There is a gradual contact between the aplite zone and the spodumene zone with minor oxide minerals along the contact. The spodumene zone contains a randomly oriented box-work texture of pink and green spodumene with interstitial white potassium feldspar, quartz and minor cassiterite. Cleavelandite, minor spessartine and rare brown radioactive minerals invade the spodumene zone due to a transition with the aplite zone.

The cleavelandite-rich zone contains abundant coarse-grained cleavelandite (up to 90 volume %) and interstitial fine-grained green rubidium-poor and cesium-poor muscovite (up to 10 volume %), minor spessartine, local pink spodumene, local oxide minerals and cassiterite next to the quartz core. A single coarse-grained, zoned, beryl crystal (22 cm wide) with a pink core and green rim occurs in cleavelandite between the aplite zone and the quartz core. Cleavelandite embays and invades the edges of the beryl crystal. Coarse-grained green muscovite (13 cm across by 4.5 cm thick) with orange spessartine inclusions (up to 6 mm) and cleavelandite occurs along the edges of the quartz core. Quartz megacrysts contain interstitial pods of cleavelandite, coarse spessartine and minor medium-grained green muscovite. This texture represents a transition between the cleavelandite-rich zone and the quartz core.

Electron microprobe investigation of the black oxide minerals in the cleavelandite-rich zone indicates that they are mostly manganocolumbite (Figure 6.10) with an average Ta_2O_5 content of 26.85 weight % and a range of 11.92 to 39.45 weight % Ta_2O_5 and, rarely, ferrocolumbite (Breaks, Selway and Tindle, in press). The manganocolumbite, however, reveals a manganese-suite trend to highly evolved compositions in terms of the Mn/(Mn+Fe) ratio that varies between 0.661 and 0.965. Microlite occurs as patch-like domains within manganocolumbite and is interpreted to have developed during late albitization of the pegmatite. Strüverite [(Ti, Ta, Fe)O_2] (11 to 12 weight % Ta_2O_5) has exsolved ferrocolumbite and manganocolumbite (9 to 12 weight % Ta_2O_5) and tantalum-bearing cassiterite (0.2 to 0.6 weight % Ta_2O_5) inclusions. Euhedral pyrite cubes have been replaced along their rims by hematite.

The lepidolite + cleavelandite pod completely enveloped by the quartz core. The lepidolite pod contains abundant cleavelandite (50 volume %) and lepidolite (40 volume %), and minor quartz (10 volume %) and rare oxide minerals. Bulk analysis of the lepidolite + cleavelandite pod shows that it is enriched in Li (2.2 weight % Li_2O), Rb (0.7 weight % Rb_2O), Zn (339 ppm), Nb (63 ppm) and Sn (60 ppm).

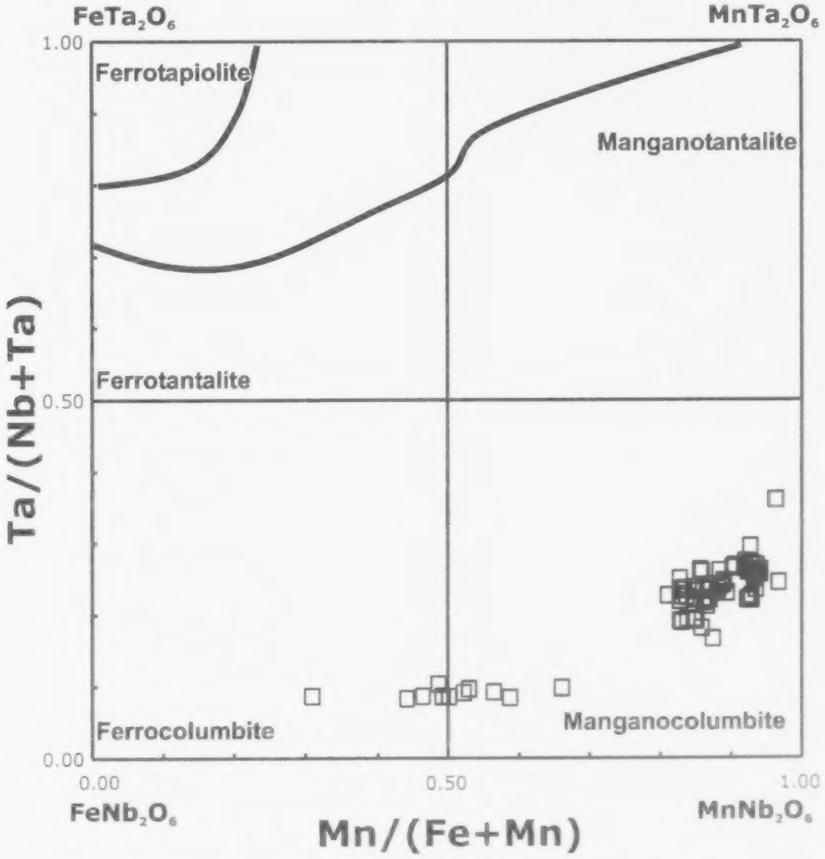

Figure 6.10. Columbite-tantalite quadrilateral plot for the Lowther Township pegmatite. Compositional gap between ferrotapiolite and ferrotantalite is based on 5200 compositions of columbite-tantalite and tapiolite from Ontario.

A single blocky white potassium feldspar crystal (40 by 70 cm) with an oxide mineral crystal and minor green muscovite occurs next to the quartz core. It is not known if this represents an additional pegmatite zone or is just an isolated potassium feldspar crystal.

Previous work by Breaks, Selway and Tindle (in press) examined the bulk compositions of coarse-grained muscovite, potassium feldspar and beryl in the Lowther Township pegmatite. Bulk analysis of coarse muscovite books gave values of 5515 ppm Rb, 1155 ppm Li, 375 ppm Nb, 247 ppm Cs and 54 ppm Ta. Three analyses of blocky potassium feldspar gave values of 971 to 3725 ppm Rb and 82 to 305 ppm Cs. Beryl contains 330 ppm Rb, 1728 ppm Li, 1.6 weight % Na_2O and an exceptionally high Cs_2O content of 2.6 weight %. Such a cesium level is considered highly evolved and closely compares with Cs_2O contents in beryl from the Tanco pegmatite (2.47 to 3.27 weight % Cs_2O: Černý et al. 1981, p.114).

Exploration Considerations

The area merits careful prospecting for more rare-element pegmatites, such as the Lowther Township complex-type pegmatite. Exploration is highly recommended in Shetland Township where a beryl-type pegmatite dike was found to contain highly anomalous tantalum levels of 78 ppm Ta coupled with a highly evolved Nb/Ta ratio of 0.77, the highest such values thus far encountered in any bulk rock sampled analyzed during the present project. The sodic pegmatite dike at locality 02-JBS-16 could represent part of a swarm of pegmatites that was generated from a nearby small mass of peraluminous pegmatitic granite at locality 02-JBS-17.

However, poor exposure will render success difficult and hence prospectors should consider the following

- The pegmatitic granite masses are erosionally resistant relative to their metasedimentary host rocks and commonly stand out as low rounded hills. This is evident for the parent pegmatitic granite that hosts the Lowther Township pegmatite which is marked by a 200 by 250 m topographic high that has about 30 m of local relief. The 1:50 000 scale topographic map of Lowther Township and adjacent townships reveal numerous ovoid topographic highs that could represent other, currently undocumented fertile, pegmatitic granite masses with internal rare-element pegmatites.
- Recognition of boulders composed of mineralogically evolved pegmatitic granite (i.e., bearing muscovite, tourmaline and spessartine garnet) should also be considered as a prospecting aid.

QUETICO–WABIGOON SUBPROVINCIAL BOUNDARY ZONE

This area of the Quetico Subprovince, which is accessed by Highway 11 and ancillary logging roads, was examined mainly in the vicinity of the Pagwachuan River system (*see* Figure 6.1).

General Geology

No published reconnaissance or detailed geological maps are available for the area that the authors sampled, as Map 2469 covers an area to the west of our sample locations (Amukun 1983). The geology along Highway 11, within 27 km of the Quetico–Wabigoon subprovincial boundary zone, largely comprises high-grade layered metasedimentary migmatite intruded by various granitic rocks:

- biotite-bearing, grey to pale pink, coarse-grained trondhjemite that is gradational into pegmatitic masses and is intruded by related, fine-grained biotite granite dikes. These rocks are locally deformed as indicated by foliation and lineation structures. Exemplified by locality 02-FWB-01 (UTM: 642741E, 5513400N, Zone 16).
- biotite and garnet-biotite potassic pegmatite that intrudes metawacke and likely postdates the grey trondhjemite rocks. Exemplified by locality 02-FWB-03 (UTM: 620081E, 5513510N, Zone 16).
- late, undeformed, sodic and potassic pegmatite dikes, 10 cm to 1.5 m thick, that contain muscovite, apatite, garnet and black tourmaline. Exemplified by locality 02-FWB-05 (UTM: 645232E, 5513350N, Zone 16).

Tourmaline is common in granite and potassic pegmatites along Highway 11 from the Quetico–Wabigoon subprovincial boundary zone east to the Pagwa Quarry. Locality 02-JBS-111 (the "Romeo" outcrop, UTM: 615020E, 5513545N, Zone 16) is composed of very coarse-grained biotite granite with biotite blades up to 19 cm long and garnet-tourmaline-biotite leucogranite. The biotite leucogranite contains garnet + fine-grained tourmaline stringers, isolated coarse-grained black tourmaline, coarse-grained beige potassium feldspar and minor green apatite. The biotite leucogranite has massive fine-grained tourmaline coating fracture planes.

Locality 02-JBS-110 (UTM: 616300E, 5513430N, Zone 16) consists of pink biotite granite intruding metasedimentary rocks. The biotite granite contains pink potassium feldspar, green plagioclase, quartz, biotite and minor green apatite, black tourmaline and garnet. Similar to locality 02-JBS-110, vertical fracture planes within this biotite granite are coated with massive fine-grained black tourmaline and minor apatite and muscovite. The origin of these tourmaline-coated fracture planes is iron-rich hydrothermal fluids from the metasedimentary host rock.

A small outcrop of pink biotite granite occurs on South Pagwachuan Road (UTM: 617083E, 5510519N, Zone 16). The biotite granite contains graphic pink potassium feldspar, garnet + biotite clots in stringers and tourmaline veinlets. Tourmaline was also found in a 3 cm wide quartz vein intruding the biotite granite. This biotite granite resembles the biotite leucogranite with garnet + tourmaline stringers in locality 02-JBS-111.

Of significance for exploration is locality 02-FWB-03 (UTM: 620082E, 5513510N, Zone 16), on Highway 11, where garnet-biotite potassic pegmatite masses intrude metawacke. The potassic pegmatite reveals locally advanced fractionation into 5 cm by 1 m quartz-rich patches that contain abundant black tourmaline and a single, 1 cm diameter, crystal of pale green beryl. The beryl crystal was removed for further mineral chemical investigation. Thus, biotite potassic pegmatites, that otherwise could be deemed as "primitive looking" are, in fact, capable of at least locally fractionating into beryl-type rare-element mineralization. The same outcrop reveals important temporal relations whereby late, undeformed, apatite-garnet-muscovite-black tourmaline potassic pegmatite dikes crosscut the biotite potassic pegmatite (Photo 6.4).

PAGWA QUARRY

This large quarry, excavated by Villeneuve Construction of Hearst, and located just west of the Pagwachuan River bridge on Highway 11, provides a unique opportunity to examine the three-dimensional aspect of peraluminous granitic pegmatite masses hosted in metawacke within a subprovince boundary zone context (UTM: 626630E, 5513683N, Zone 16). The main rock type is white garnet-biotite potassic pegmatite that has been fractionated into quartz-rich patches with impressive blocky pink potassium feldspar and coarse-grained columnar black tourmaline crystals up to 2 cm in diameter (Photo 6.5a). An intermediate zone in this main body is a tourmaline-garnet-biotite potassic pegmatite (locality 02-JBS-09-10), which contains very coarse-grained pale pink potassium feldspar, quartz, fine-grained red garnet, fine-grained biotite, tourmaline and rare fine-grained green apatite. The tourmaline shows 2 textures: graphic tourmaline + quartz intergrowths and columnar black tourmaline up to 4 cm long. Bulk analyses of this intermediate zone indicate elevated barium, strontium and zirconium contents (1048 ppm Ba, 174 ppm Sr and 202 ppm Zr).

The central part of the quarry wall exposes a vertical, deep pink to red, dike of tourmaline-biotite potassic pegmatite (Photo 6.5b). The red colouration is caused by hematite staining of the abundant potassium feldspar in this dike. The dike also contains 5 to 10 volume % dark green mica aggregates, which may be altered cordierite. The bulk analysis of this dike (locality 02-JBS-09-06) has low Si contents (53.51 weight % SiO_2), high Ca and Fe contents (8.44 weight % CaO, 2.63 weight % Fe_2O_3) and elevated Nb contents (81 ppm Nb).

The eastern end of the quarry wall exposes 3, vertical, white, potassic pegmatite dikes and 1 horizontal potassic pegmatite dike (Photo 6.5c). The vertical dike, labelled "A" in Photo 6.5c, consists of a 1 m thick coarse-grained biotite granite wall zone and a garnet-biotite-muscovite-bearing potassic pegmatite main zone. Bulk analyses of the wall zone (locality 02-JBS-09-02) indicate elevated barium and strontium contents (1247 ppm Ba and 222 ppm Sr). The late discordant dike, labelled "B" in Photo 6.5c, is 15 to 30 cm wide and consists of an aplite border zone and pale pink tourmaline-biotite potassic pegmatite with elevated rubidium contents (336 ppm Rb) (locality 02-JBS-09-04).

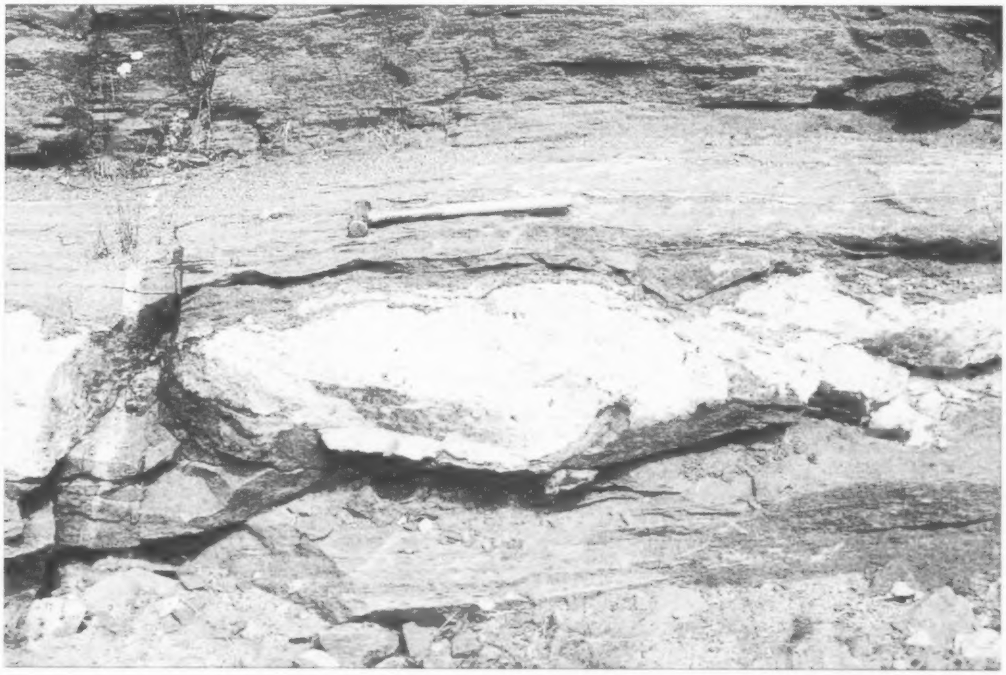

Photo 6.4. Late, undeformed, apatite-garnet-muscovite << black tourmaline potassic pegmatite dikes crosscut a biotite potassic pegmatite hosted by metawacke.

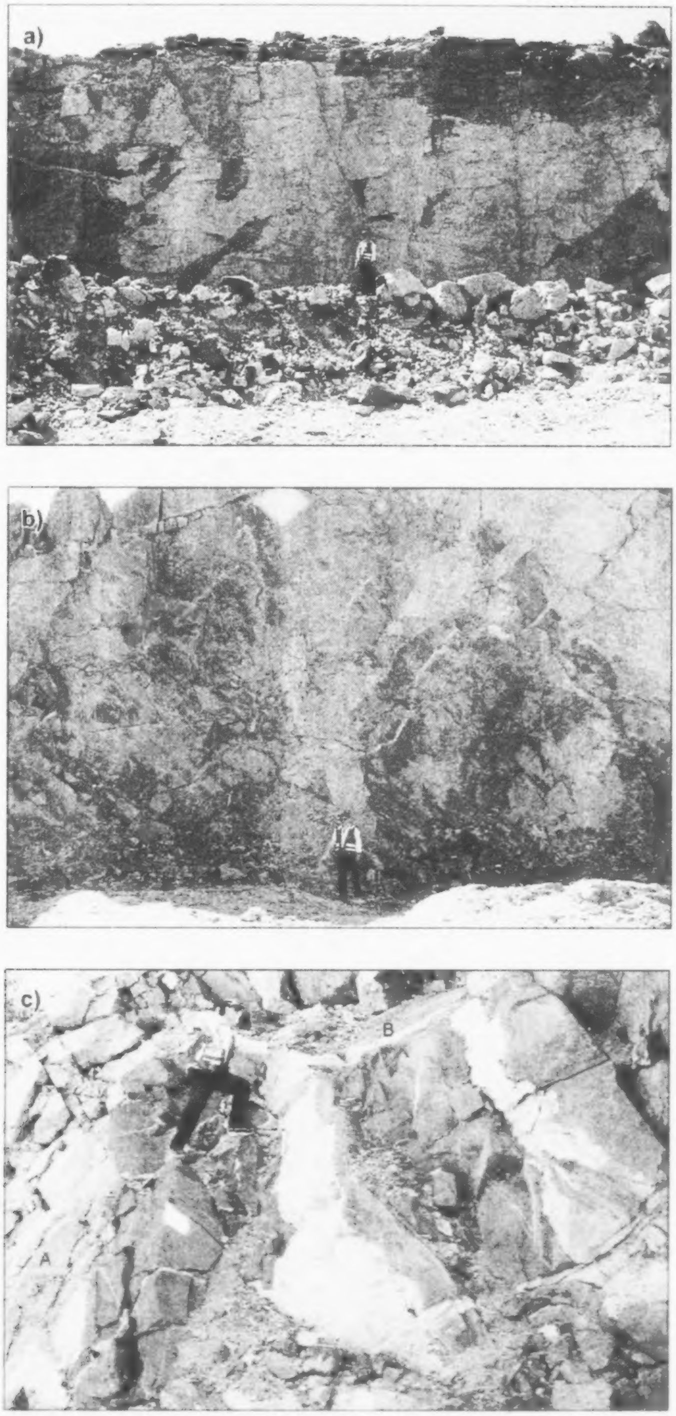

Photo 6.5. **a)** White garnet-biotite potassic pegmatite body in the western end of the Pagwa quarry wall. **b)** F.W. Breaks is standing in front of a deep pink potassic pegmatite vertical dike. **c)** Potassic pegmatite dikes in the eastern end of the Pagwa quarry wall. Label A indicates vertical potassic pegmatite dike, and label B indicates late discordant potassic pegmatite dike.

Exploration Considerations

Abundance of late tourmaline-rich dikes and an earlier generation of tourmaline associated with biotite and garnet-biotite potassic pegmatite masses, as exemplified by the Pagwa quarry, represents a positive feature for rare-element exploration with the Quetico–Wabigoon subprovincial boundary zone. Boron, present in the tourmaline crystal structure, could have been an important volatile for complexing of the various rare elements during the genesis and emplacement of granite and related pegmatite dikes in this region. Hence, more prospecting is warranted in the area for possible more evolved tourmaline-bearing pegmatites that could contain lithium- and tantalum-rich minerals.

OPATICA SUBPROVINCE

Rare-element mineralization in the Opatica Subprovince is currently known only at the Case pegmatite in the Lake Abitibi area (*see* Figure 6.1). Nevertheless, this spodumene-subtype pegmatite comprises the fifth largest lithium-rich pegmatite in the Superior Province of Ontario.

Case Pegmatite

This swarm of 3 pegmatites has witnessed intermittent exploration interest since its discovery in 1959 (Lumbers 1962, p.29). A previous investigation generally characterized the mineralogy that included columbite-tantalite and pollucite (Nickel 1963). A bulk sample of pollucite-bearing material contained 5.79 weight % Cs_2O (Nickel 1963). Recent work (Horne 2000) involved extensive stripping over most of the exposed strike length of 290 m, followed by channel sampling and total field magnetic and magnetic gradient ground geophysical surveys. Recently, Platinova Resources (Platinova Resources, news release, August 8, 2001, www.platinova.com) optioned the property in order to assess the tantalum potential of the Case pegmatite system. An average content of 0.024 weight % Ta_2O_5, with a range of 0.003 to 0.068 weight %, was calculated from 16 grab samples selected by Horne (2000). Recent results from channel sampling and a limited diamond-drill program established an average of 0.024 weight % Ta_2O_5 across 8 m in the Central Dike and a range of 0.011 weight % (over 1 m) to 0.032 weight % Ta_2O_5 (over 7.7 m) for the North Dike (Platinova Resources, news release, October 4, 2001).

The Case pegmatite system is hosted in the southeastern part of the Case batholith, an extensive 50 by 85 km, ovoid granitic complex that is apparently part of the Opatica Subprovince (Jackson and Fyon 1991). The immediate host rocks of the pegmatite dikes consist of massive to subtly foliated, biotite tonalite that is characterized by biotite-rich orbicules that range in diameter from 1 to 7 cm. Such entities are classified as proto-orbicules (Leveson 1966) and, commonly, exhibit a linear alignment that is parallel to the weak foliation of its tonalite host. The foliation of the biotite in the tonalite is perpendicular to the contact with the pegmatite.

The biotite tonalite host rock for the Case pegmatite system was intruded by early aplite dikes which were subsequently crosscut by the pegmatite dikes (Photo 6.6a). A metasomatic halo exists in the tonalite up to 10 cm from the contact with the pegmatite. The tonalite close to the contact contains green muscovite, whereas the unaltered tonalite contains biotite.

The geology of the Central and North dikes has been previously discussed by Breaks, Selway and Tindle (2001, in press). A detailed discussion of the mineral chemistry of these dikes was also completed by Breaks, Selway and Tindle (in press).

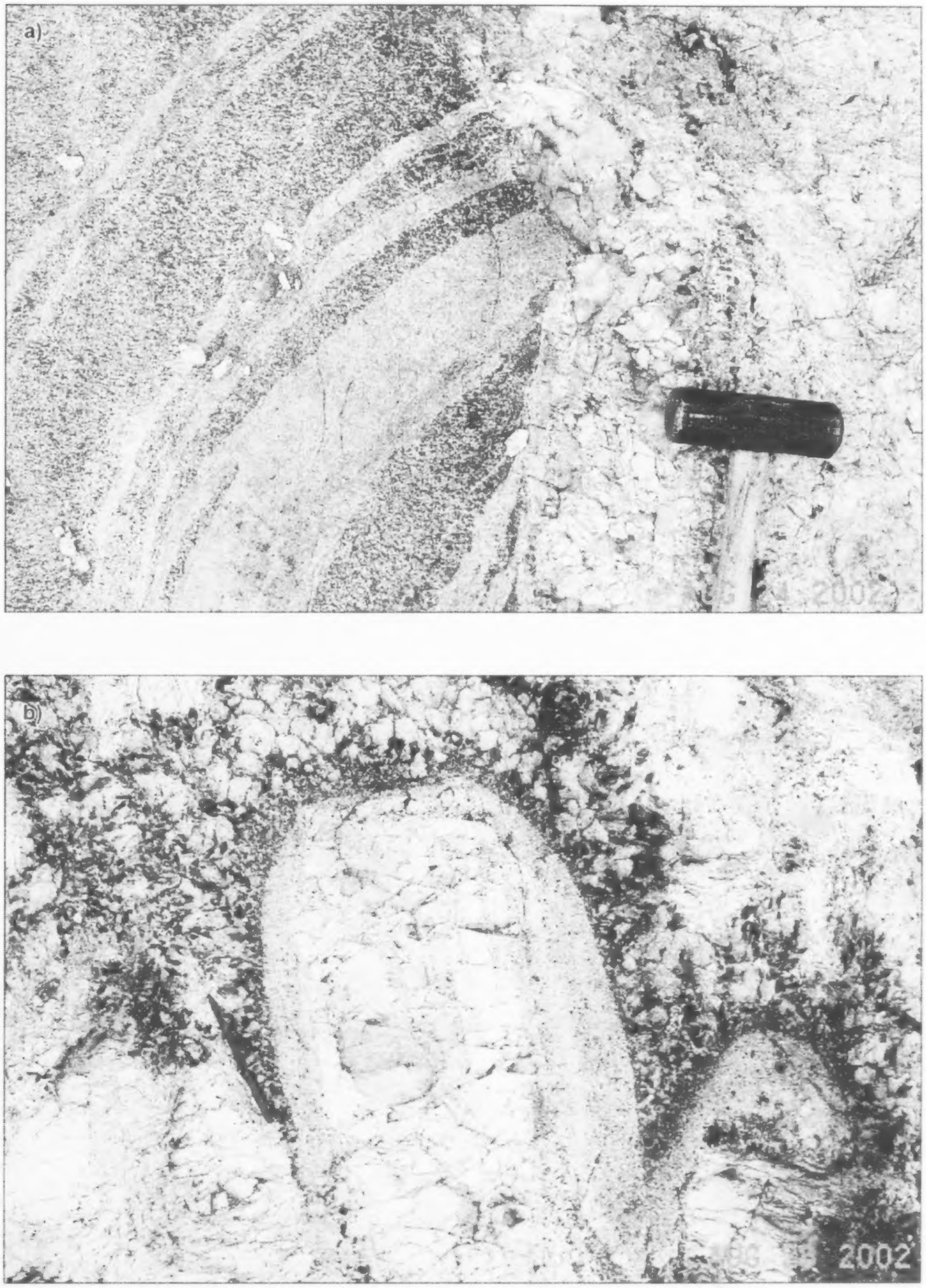

Photo 6.6. a) Case South Dike easternmost outcrop: biotite tonalite crosscut by early aplite dikes, both of which are crosscut by the pegmatite. **b)** Case South Dike easternmost outcrop: corona with a blocky potassium feldspar centre, surrounded by muscovite aplite, surrounded by interstitial quartz + muscovite intergrowth. Note the pen for scale.

The pegmatite swarm, which strikes at 060 to 070° and dips 40 to 60° north, consists of 3 *en échelon* dikes exposed within a 260 by 350 m area situated immediately east of the contact between the Case batholith and Scapa metasedimentary rocks (Lumbers 1962):

- South Dike (10 m thickness; 250 m minimum strike length)
- Central Dike (39 m thickness; 350 m minimum strike length)
- North Dike (12 m thickness; 100 m minimum strike length)

The Central and North dikes are very similar in mineral assemblage and pegmatite zonation. The most significant difference between the South Dike and the Central and North dikes is that spodumene is absent in the South Dike, but abundant in the North and Central dikes. Green beryl is locally abundant in all 3 dikes. Thus, the Case pegmatite system increases in fractionation from the beryl-type South Dike to the complex-type, spodumene-subtype Central and North dikes. This increase in fractionation is supported by bulk analyses in 5 potassium feldspar analyses: South Dike (3807 to 3932 ppm Rb; 155 to 182 ppm Cs; K/Rb = 28-29); Central Dike (5448 to 6309 ppm Rb, 350 to 560 ppm Cs, K/Rb = 17-20) and the North Dike (7106 ppm Rb, 1000 ppm Cs, K/Rb = 16).

CASE SOUTH DIKE

The South Dike is exposed in 3 outcrops: 1) next to the road (UTM: 578365E, 5431358N, Zone 17), 2) the easternmost outcrop in the bush (UTM: 578360E, 5431524N, zone 17), and 3) the main outcrop in the bush (UTM: 578374E, 5431329N, Zone 17).

The easternmost outcrop consists of a potassic pegmatite dike, which ranges in width from 0.8 to 10 m wide. The most interesting texture is a corona with a large single crystal of potassium feldspar surrounded by green muscovite aplite with minor garnet layer, surrounded by quartz + coarse green muscovite intergrowth (Photo 6.6b). Quartz + muscovite intergrowth is interstitial to several potassium feldspar-centred coronas and blocky potassium feldspar crystals and contains minor oxide minerals. The blocky potassium feldspar is slightly albitized along its margins and fractures within the crystal. Oxide minerals and garnet occur in the aplite which invades the blocky potassium feldspar crystals. Local green beryl occurs the blocky potassium feldspar zone. The eastern outcrop also contains albite + muscovite + quartz pod surrounded by rounded aplite pod. Euhedral blocky potassium feldspars (up to 54 cm long) occur in a quartz pod.

The outcrop next to the road consists of a potassic pegmatite dike, which contains the following pegmatite zones: albite + coarse muscovite + quartz zone with local green beryl, garnet aplite pods and blocky potassium feldspar + quartz zone. The blocky potassium feldspar (up to 80 cm long by 36 cm wide) is albitized along its margins. Oxide minerals occur in the aplite that invaded the blocky potassium feldspar.

The main outcrop of the South Dike differs from the easternmost outcrop in that green beryl and garnet aplite is more abundant than in the easternmost outcrop. Pegmatitic zoning is also more distinct in the main outcrop than in the easternmost outcrop. The main outcrop contains

- aplite border zone
- quartz + coarse green muscovite zone with minor oxide minerals and local beryl
- albite + coarse muscovite + quartz zone with local abundant apatite (up to 20 volume %) and minor beryl and oxide minerals
- layered aplite with green muscovite and/or garnet, and minor oxide minerals and apatite
- potassium feldspar + green muscovite + quartz zone
- blocky albitized potassium feldspar + quartz + beryl (up to 9 cm long)

CASE CENTRAL DIKE

The Central Dike progressively widens from 10 to 39 m in a west to east direction and, thus, remains open to the east beyond the limits of visible outcrop. The main exposure, within the eastern part of the dike (UTM co-ordinates: 578247E, 5431660N; Zone 17), reveals a subtly zoned pegmatite that consists of the following units:

- sodic aplite border zone, 5 to 20 cm thick
- quartz + green muscovite zone
- quartz + green muscovite + potassium feldspar granitic zone and layers
- spodumene-rich zone (muscovite-potassium feldspar-quartz-green spodumene-albite)
- quartz-rich core zone
- lime green muscovite-rich patches
- late dikes of spodumene pegmatite

The sodic aplite border zone occurs along both the north and south contacts as a sugar-textured, fine-grained white to pale pink friable rock. Minor phases include red garnet, blue fluorapatite and sparse black specks of tantalum-niobium oxide minerals. The aplite contains garnet stringers and along the northern contact is layered with muscovite-rich and muscovite-poor layers. The aplite also contains granitic layers composed of quartz, muscovite and potassium feldspar (Photo 6.7a). Local green beryl tends to occur along the contact between the aplite and quartz + muscovite + potassium feldspar zone.

The spodumene-rich zone contains very coarse-grained green and white spodumene, blocky white potassium feldspar, albite, quartz; local muscovite, beryl, oxide minerals and spessartine and rare brown zircon. One particular spot in the medium-grained spodumene zone has abundant platy oxide minerals. The average grain size of the spodumene-rich zone increases from medium-grained to very coarse-grained as it grades in the quartz-rich core zone. Toward the centre of the dike, a spodumene-rich zone assumes dominance that subsequently grades into a 5 to 10 m by 90 m quartz-rich core zone. This zone consists of 70 to 80% massive white quartz and contains the coarsest blocky potassium feldspar (82 by 95 cm) and spodumene megacrysts (5 by 70 cm) in the entire pegmatite system and local green beryl (up to 6 cm across) and spessartine. Small, blob-like masses, rich in lime green muscovite (80%) and augmented by orange spessartine, albite and spodumene, occur sparsely in the core zone. These minerals (spodumene) range in size from 5 by 8 cm to 60 cm by 1.3 m. Rust-stained cavities characterize spodumene megacrysts within and proximal to these muscovite-rich domains. The cavities are due to inclusions of weathered sphalerite. Late dikes of spodumene pegmatite transect the aplite border zone and progress into the tonalite host rocks, thus, indicating a relatively early crystallization for the aplite that could have resulted in a rapid, pressure quench crystallization (Jahns 1982).

The western part of the Central Dike (UTM: 578055E, 5431567N, zone 17) consists of an aplite border zone, spodumene granite and garnet aplite pods and a blocky potassium feldspar with interstitial quartz + muscovite zone. The western part of the Central Dike, however, reveal a striking contrast to the eastern part in the greater abundance of sodic aplite layered with coarse-grained spodumene granite and the presence of quartz-ballpeen-textured dark mica-albite pods. There are also only small patches of quartz-rich core zone material, which have entirely disappeared at the western exposure of the Central Dike.

The spodumene granite zone contains fine- to medium-grained green spodumene, quartz, feldspar, minor muscovite and local green beryl (up to 5 cm). Green spodumene granite pods are rimmed by a line of muscovite and enveloped in garnet aplite. Garnet aplite pods are rimmed by a line of muscovite and enveloped by green spodumene granite (Photo 6.7b). Muscovite also forms a line separating the green spodumene granite zone and the quartz + muscovite + potassium feldspar granitic zone.

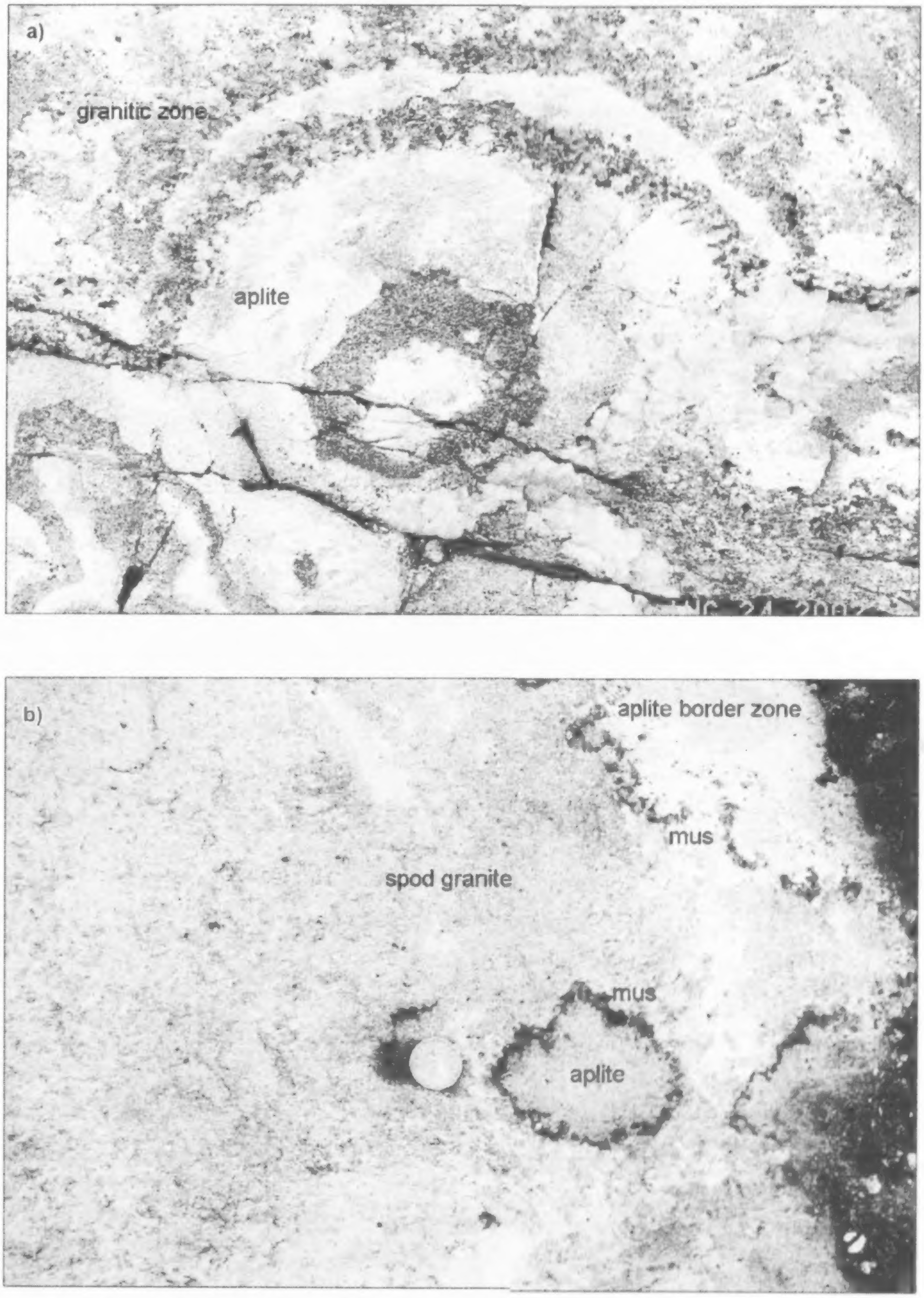
a)
granitic zone
aplite
b)
aplite border zone
mus
spod granite
mus
aplite

Photo 6.7. a) Case Central Dike, southern contact: alternating layers of aplite and the granitic zone. **b)** Western part of Case Central Dike: aplite pods rimmed by a line of muscovite and enveloped by spodumene granite. A line of muscovite also occurs along the contact between the spodumene granite and the aplite border zone.

Mineral Chemistry

Oxide minerals occur in the aplite border zone and the quartz-rich core zone of the main part of the Central Dike (Figure 6.11). The fine-grained oxide minerals in the garnet-muscovite-fluorapatite aplite border zone are ferrocolumbite with an average of 16.36 weight % Ta_2O_5. This is the most primitive oxide composition in the Case pegmatite, whereas the oxide minerals in the quartz-rich core zone have the most fractionated compositions in the pegmatite: manganocolumbite (38.73 weight % Ta_2O_5), manganotantalite patches (average 62.79 weight % Ta_2O_5) and microlite (average 69.0 weight % Ta_2O_5).

Oxide minerals occur in the aplite border zone and the spodumene granite zone of the western part of the Central Dike. The fine-grained oxide minerals in the garnet aplite border zone are mostly ferrocolumbite with a thin manganocolumbite rim (average 28.26 weight % Ta_2O_5). Microlite with 70.0 weight % Ta_2O_5 is also present in the aplite border zone. Oxide minerals (2 by 4 mm) in layered garnet-muscovite aplite plots in the centre of the columbite-tantalite quadrilateral and is complexly zoned with iron- and tantalum-enriched rims. The composition ranges from manganotantalite core, manganocolumbite, ferrocolumbite and ferrotantalite rims with an overall average of 53.08 weight % Ta_2O_5. Most of the oxide minerals in the spodumene granite ranges in composition from ferrocolumbite to manganocolumbite with minor uranoan microlite. In sample 01-JBS-159-01, the platy oxide minerals in medium- to coarse-grained spodumene granite are zoned with tantalum-poor relict cores (ferrocolumbite to manganocolumbite, average of 24.44 weight % Ta_2O_5) and tantalum-rich rims (ferrotantalite, average 49.70 weight % Ta_2O_5).

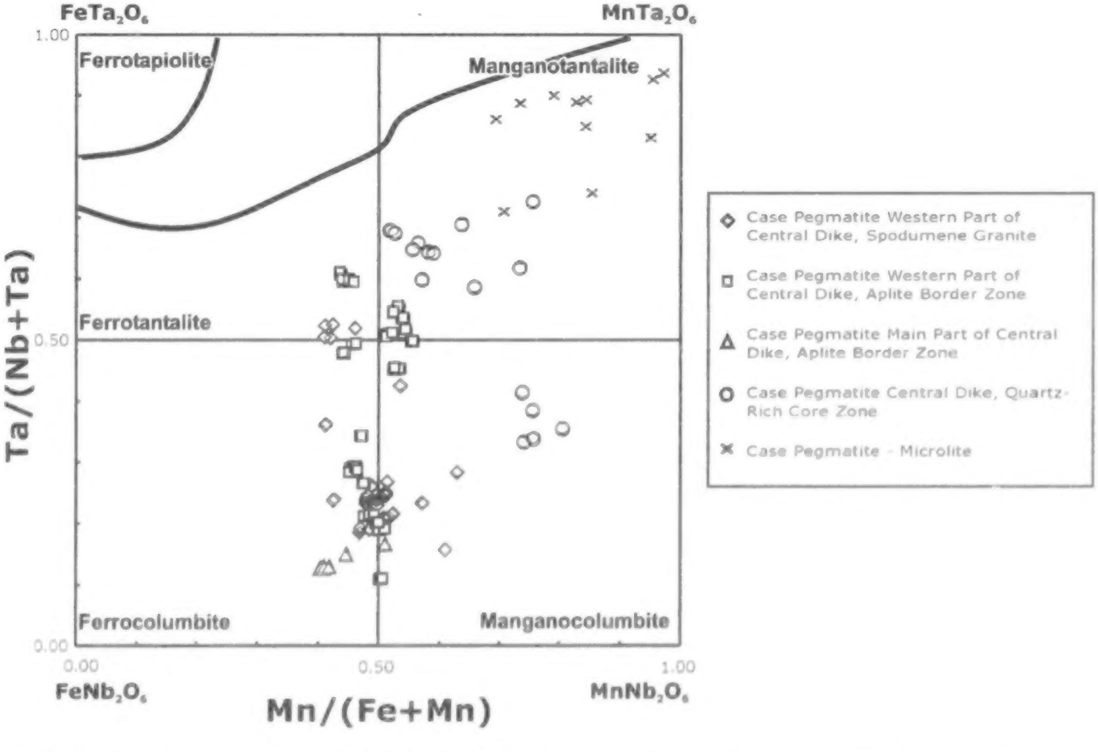

Figure 6.11. Columbite-tantalite quadrilateral plot for the Case pegmatite. Compositional gap between ferrotapiolite and ferrotantalite is based on 5200 compositions of columbite-tantalite and tapiolite from Ontario.

CASE NORTH DIKE

The North Dike (UTM: 578131E, 5431641N, Zone 17) is located very close the Central Dike. It is characterized by layering parallel to the its strike (Photo 6.8). The North Dike consists of the following pegmatite zones:

- garnet aplite border zone (minor oxide minerals)
- quartz + muscovite + potassium feldspar granitic zone
- aplite pods
- quartz-rich core zone with euhedral white potassium feldspar
- spodumene-rich zone (muscovite-potassium feldspar-quartz-spodumene)

Local green beryl occurs along the contact between the aplite border zone and a thin quartz-rich layer. Two steel-blue molybdenite pods (2 cm and 1 cm diameter) occur in the granitic zone. Aplite pods are rimmed by green muscovite. The spodumene in the spodumene-rich zone is very coarse-grained with blades up to 70 cm long by 5 cm wide.

Mineral Exploration

The newly documented pattern of beryl-type to complex-type, spodumene-subtype fractionation, coupled with the potassium feldspar mineral chemistry, within the Case pegmatite dike swarm is significant. This indicates that pegmatite fractionation increased from south to north and, therefore, it is possible that even more fractionated rare-element-mineralized dikes, enriched in cesium and tantalum mineralizaton, could lie north of the North Dike within an area of poor exposure. This area is highly recommended for follow-up exploration work.

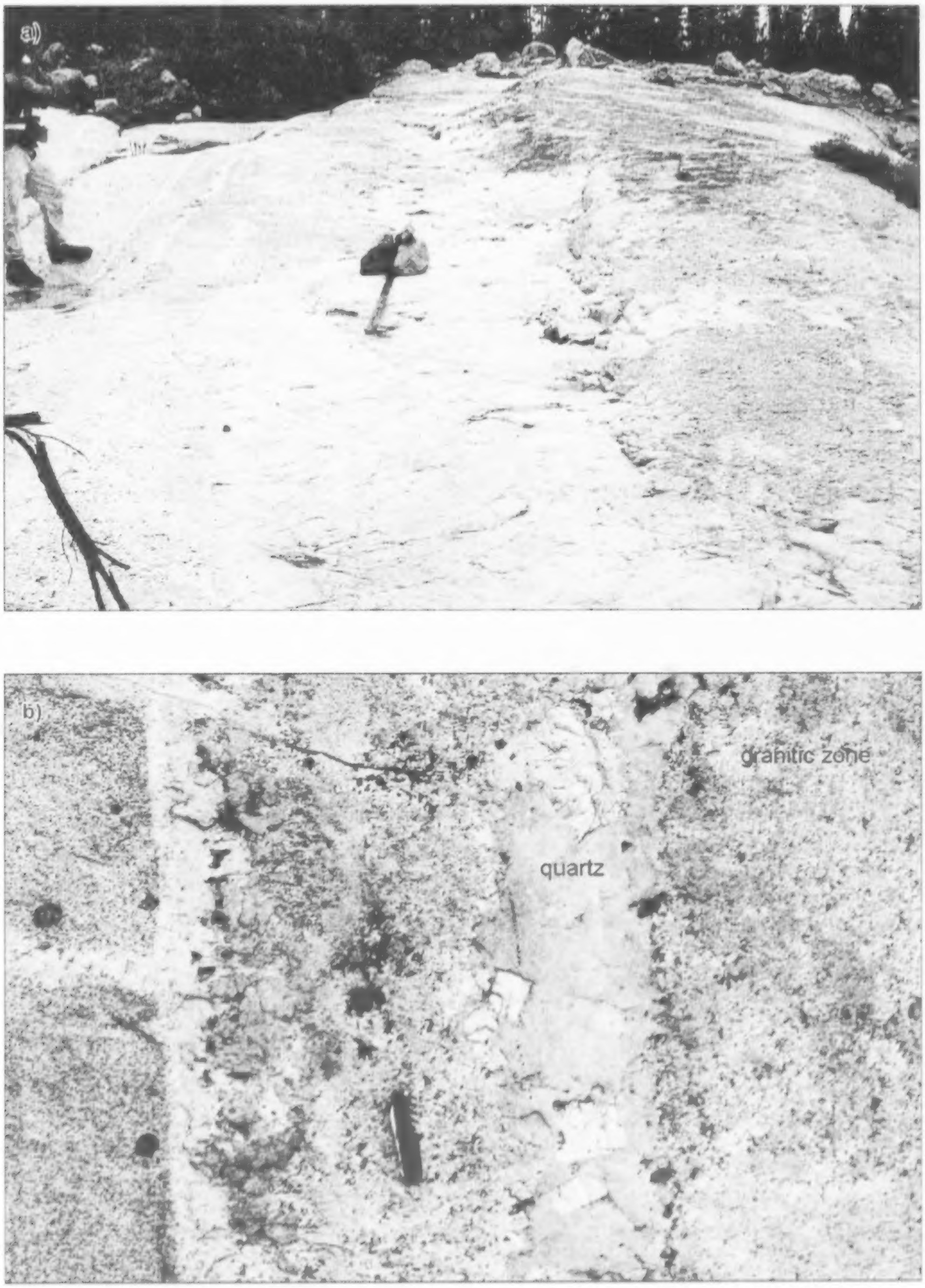

Photo 6.8. **a)** Case North Dike: F.W. Breaks is standing on the orbicular biotite tonalite host rock. The aplite border zone of the pegmatite is in front of his feet. The rocks in the centre of the photo are on top of the quartz core. The biotite tonalite host is also shown on the left side of the photo next to the grass. **b)** Case North Dike hosted by orbicular biotite tonalite (far right). Note the biotite tonalite host rock is crosscut by an earlier aplite dike. Pegmatite zones from right to left: aplite border zone, granitic zone, quartz + euhedral potassium feldspar layer and granitic zone.

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7. Project Unit 99-021. Recent Advances in Komatiite Volcanology in the Abitibi Greenstone Belt, Ontario

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INTRODUCTION

This project is part of a PhD study based at Laurentian University and the University of Ottawa, under the supervision of Drs. Michael Lesher and Anthony Fowler. The project is partially supported under an Ontario Geological Survey (OGS) – Mineral Exploration Research Centre (MERC) Collaborative Project Agreement. The principal aims of the project are to establish variations in volcanic facies of komatiite in the Abitibi greenstone belt (AGB), to test and refine current stratigraphic, tectonic and metallogenic models for the AGB (Jackson and Fyon 1991; Jackson, Fyon and Corfu 1994; Heather 1998; Ayer et al. 1997, 1999a, 1999b), and to help constrain the volcanic architecture of komatiite flow fields. The AGB was selected for study because of the excellent mineralogical and textural preservation of the rocks, the abundance of glacially polished outcrops, and the excellent geological, geochemical and geochronological database. A better understanding of the volcanic architecture of komatiite will help constrain stratigraphic, tectonic and metallogenic models throughout the AGB and may aid in the development of similar models in other greenstone belts. Three broad topics have been addressed thus far: 1) classification of komatiite lava flow facies; 2) determination of regional facies variations of komatiite in the AGB; 3) and determination of local facies variations of komatiite in the AGB. A komatiite lava flow classification has been developed to provide an internally consistent framework for the classification of komatiite in the AGB (Houlé et al. 2001a, 2001b, 2001c). Regional facies variations of komatiite in the AGB have been studied by compiling data from both the literature and from previous projects supervised by C.M. Lesher and A.D. Fowler, supplemented by field work in critical areas. Local facies variations of komatiite have been studied by detailed mapping of key areas with excellent exposure. This multi-scale, integrated approach has been critical in constraining the interpretation of komatiite facies to aid in the interpretation of the volcanic architecture of komatiite flow fields.

REGIONAL GEOLOGIC SETTING

The Abitibi greenstone belt (AGB) is located in the Superior Province, the largest Archean craton in the world. The AGB has been divided into 2 volcanic zones: the "Northern Volcanic Zone" (NVZ) and the "Southern Volcanic Zone" (SVZ) (e.g., Ludden, Hubert and Gariépy 1986). Komatiite, komatiitic basalt, and picrite occur predominantly within the SVZ.

Detailed geochronological data have been used to subdivide the AGB in Ontario into 9 stratigraphically distinct assemblages (Figure 7.1), 7 of which are dominantly volcanic and 2 of which are dominantly sedimentary (e.g., Ayer et al. 2002). Only 4 of the assemblages contain ultramafic rocks: the Pacaud assemblage (PCA), the Stoughton–Roquemaure assemblage (SRA), the Kidd–Munro assemblage (KMA), and the Tisdale assemblage (TSA). Komatiitic rocks represent only a minor proportion of each assemblage (Ayer et al. 2002; Sproule et al. 2002).

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.7-1 to 7-19.

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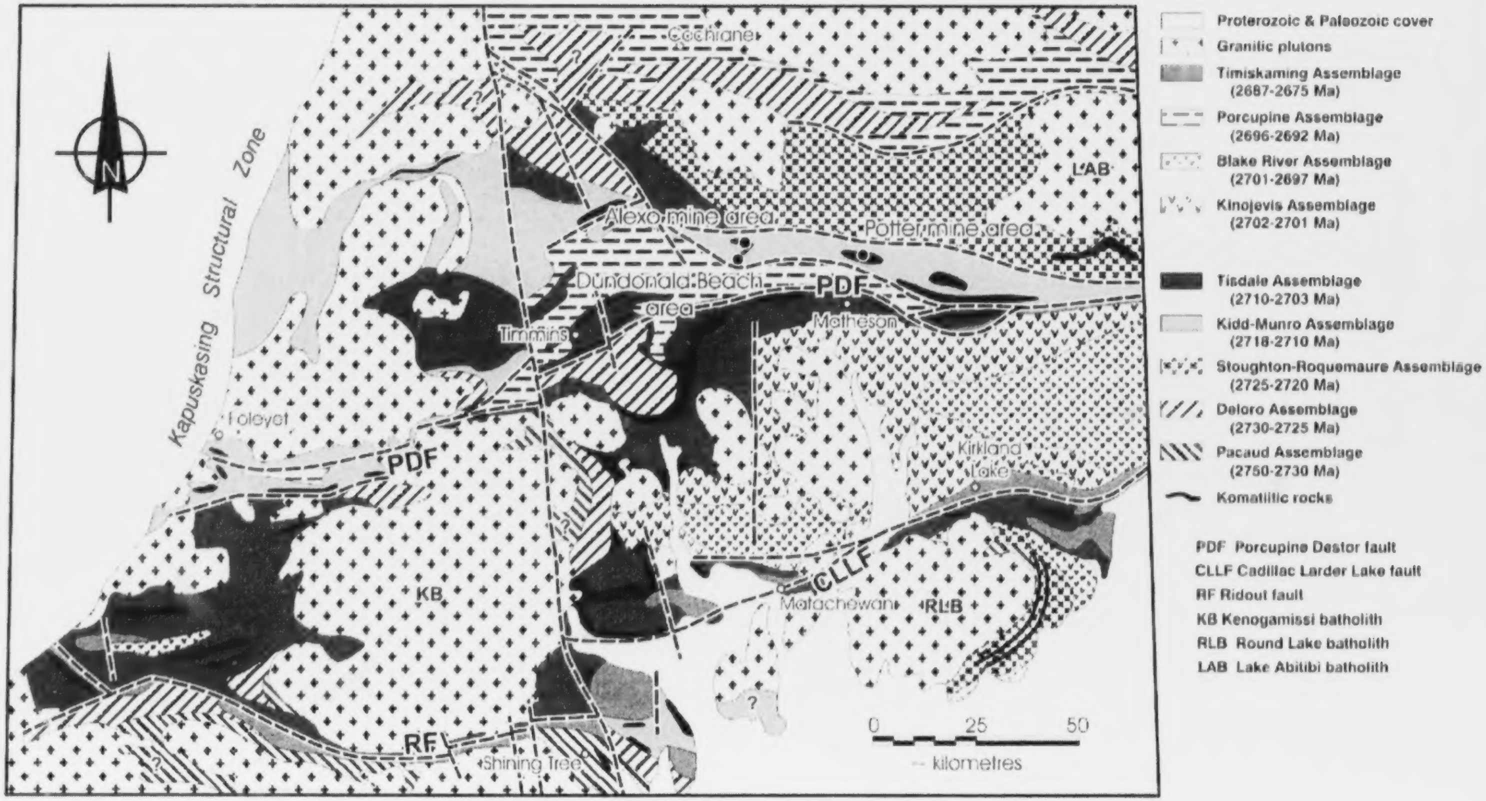
N
Kapuskasing Structural Zone
Cochrane
Alexo mine area
Potter mine area
Dundonald Beach area
Timmins
PDF
Matheson
LAB
Foleyet
PDF
KB
Kirkland Lake
CLLF
Matachewan
RLB
RF
Shining Tree
?
0
25
50
kilometres
Proterozoic & Paleozoic cover
Granitic plutons
Timiskaming Assemblage (2687-2675 Ma)
Porcupine Assemblage (2696-2692 Ma)
Blake River Assemblage (2701-2697 Ma)
Kinojevis Assemblage (2702-2701 Ma)
Tisdale Assemblage (2710-2703 Ma)
Kidd-Munro Assemblage (2718-2710 Ma)
Stoughton-Roquemaure Assemblage (2725-2720 Ma)
Deloro Assemblage (2730-2725 Ma)
Pacaud Assemblage (2750-2730 Ma)
Komatiitic rocks
PDF Porcupine Destor fault
CLLF Cadillac Larder Lake fault
RF Ridout fault
KB Kenogamissi batholith
RLB Round Lake batholith
LAB Lake Abitibi batholith

Figure 7.1. Geological map showing stratigraphic assemblages and distribution of the major komatiitic rocks in the Abitibi greenstone belt (*modified from* Ayer et al. 2002)

ALEXO MINE AREA

The Alexo Mine is located on the northeast-dipping central limb of the Dundonald fold structure, in an area that has been metamorphosed to prehnite-pumpellyite facies and contains some of the best preserved komatiite (2.7 Ga) in the world (Arndt 1986a). The stratigraphic succession comprises 4 sequences of komatiitic rocks intercalated with intermediate metavolcanic rocks (Davis 1999). Younging indicators in the komatiite (e.g., flow-top breccia, asymmetrically zoned spinifex textures, transgressive lower margins of lava channels, disseminated–net-textured–massive ore segregation profiles) and andesite (e.g., flow-top breccia, pillow geometries) consistently face northward to westward. The compositions of the andesite vary systematically from more tholeiitic in the south to more calc-alkalic in the north, indicating that the sequence is located on the same limb of the regional fold.

The iron-nickel-copper-platinum group element (PGE) sulphide mineralization at the Alexo Mine is hosted by an approximately 600 m thick (P.C. Davis, MPH Consulting Ltd., personal communication, 2002) olivine cumulate komatiite unit that is partially localized within embayments in the footwall andesite (Lowther 1950; Naldrett 1966; Davis 2001). The ores exhibit a classic magmatic ore segregation profile: a thinner lower zone of massive to semi-massive sulphide mineralization overlain by a thicker zone of net-textured and disseminated sulphide mineralization. The massive zones extend laterally for tens of metres along strike and contain 15 to 20% pentlandite, 80 to 85% pyrrhotite, and trace amounts of unevenly distributed chalcopyrite and, where oxidized, heazlewoodite and violarite (Coad 1979). Small massive to semi-massive veinlets extend into the footwall rock. Massive ores contain, on average, 5.4% Ni, 0.35% Cu, and 3.8 g/t ∑PGE (Pt+Pd+Rh+Ru+Ir+Os) in 100% sulphides, whereas net-textured and disseminated ores contain, on average, 6.4% Ni, 0.58% Cu, and 4.3 g/t ∑PGE (Pt+Pd+Rh+Ru+Ir+Os) in 100% sulphides (Barnes and Naldrett 1987; Davis 2001), implying a higher R factor (mass ratio of silicate to sulphide liquid) for net-textured and disseminated ores than for massive ores.

Evidence for Thermomechanical Erosion

Most komatiite-associated nickel-copper (±PGE) deposits exhibit geological, stratigraphic, geochemical, and/or isotopic evidence for thermomechanical erosion of footwall rocks and incorporation of crustal sulphur via devolatilization or melting of country rocks (e.g., Lesher 1989; Naldrett 1989; Lesher et al. 2001; Lesher and Keays 2002). However, Cas and Beresford (2001) and Rice and Moore (2001) have recently argued that the thermomechanical erosion did not occur.

The komatiite–andesite contacts east and west of the Alexo Mine shaft were stripped by Hucamp Mines Ltd. in 2001 and extended by Larchex Inc. in 2002, exposing the basal contact of the mineralized lava channel in glacially polished outcrops. These areas provide almost complete exposure of the well-preserved contact between the pillowed, massive, and hyaloclastic footwall andesite and the overlying mineralized cumulate komatiite unit. The following observations provide very strong, if not unequivocal, evidence of thermomechanical erosion of the footwall andesitic rocks:

- There are multiple scales and multiple orders of embayments, all of which clearly transgress the andesite without any evidence of development of a regolith, shearing, or of folding along the contact, or of folding in any of the underlying andesite or the overlying ore horizon. The first-order embayment that localizes the Alexo Mine komatiite host unit is a ~120 m wide and ~25 m deep concave depression (Naldrett 1966) that contains numerous second-order re-entrant embayments ranging from 10 to 20 m in width and from 3 to 6 m in depth (Figures 7.2A and 7.2B), and third-order embayments ranging from 10 to 30 cm in width and from 10 to 50 cm in depth (Figure 7.3A), resulting in a highly contorted lower contact that cannot have been produced by folding or faulting.

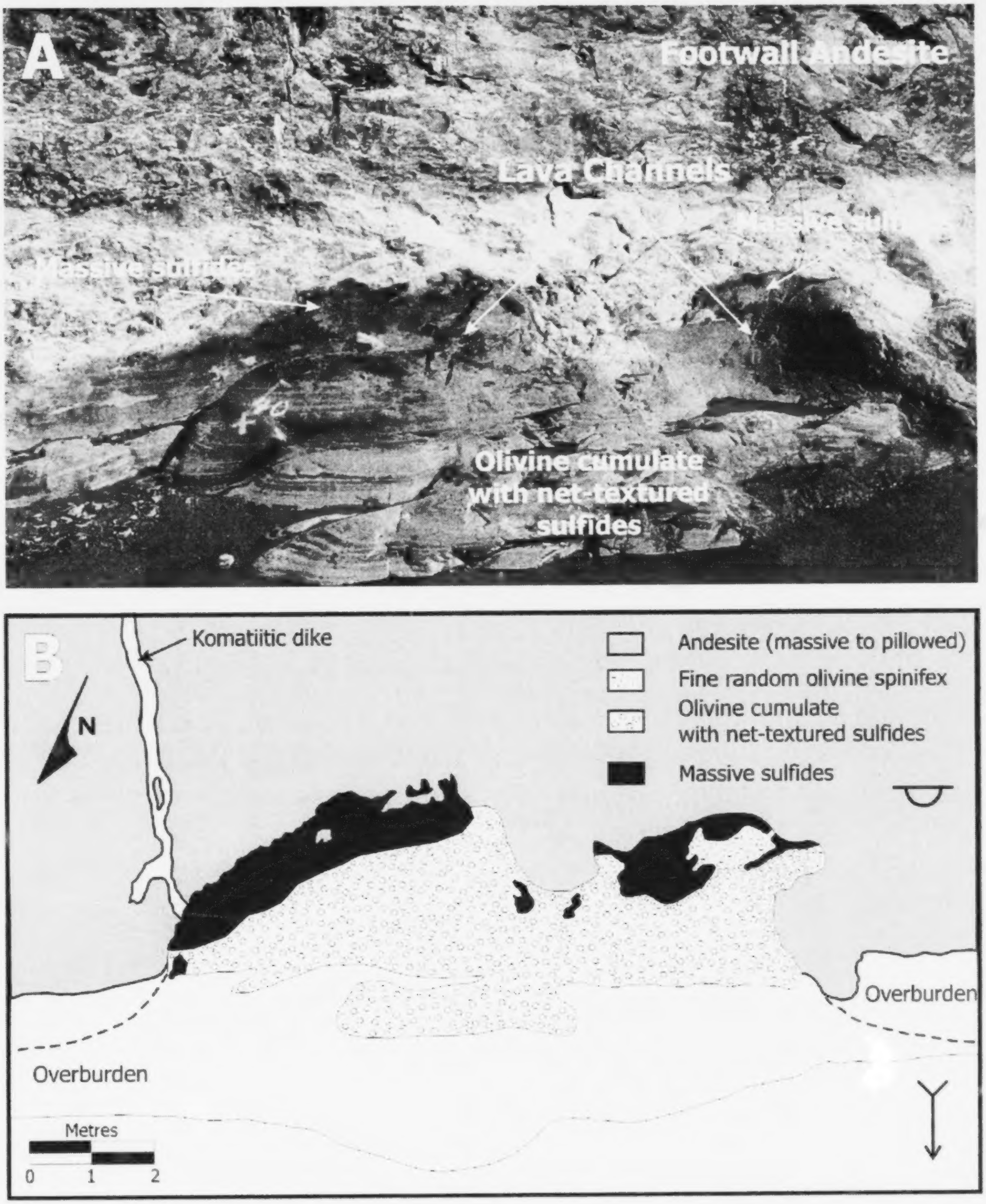
A
Footwall Andesite
Lava Channels
Massive sulfides
Massive sulfides
Olivine cumulate with net-textured sulfides
B
Komatiitic dike
N
Andesite (massive to pillowed)
Fine random olivine spinifex
Olivine cumulate with net-textured sulfides
Massive sulfides
Overburden
Overburden
Metres
0
1
2

Figure 7.2. A) Photo and **B)** map of 2 second-order embayments in the "West Area" at the Alexo Mine. A similar geometry was produced in the analog model of Huppert and Sparks (1985, Figure 12).

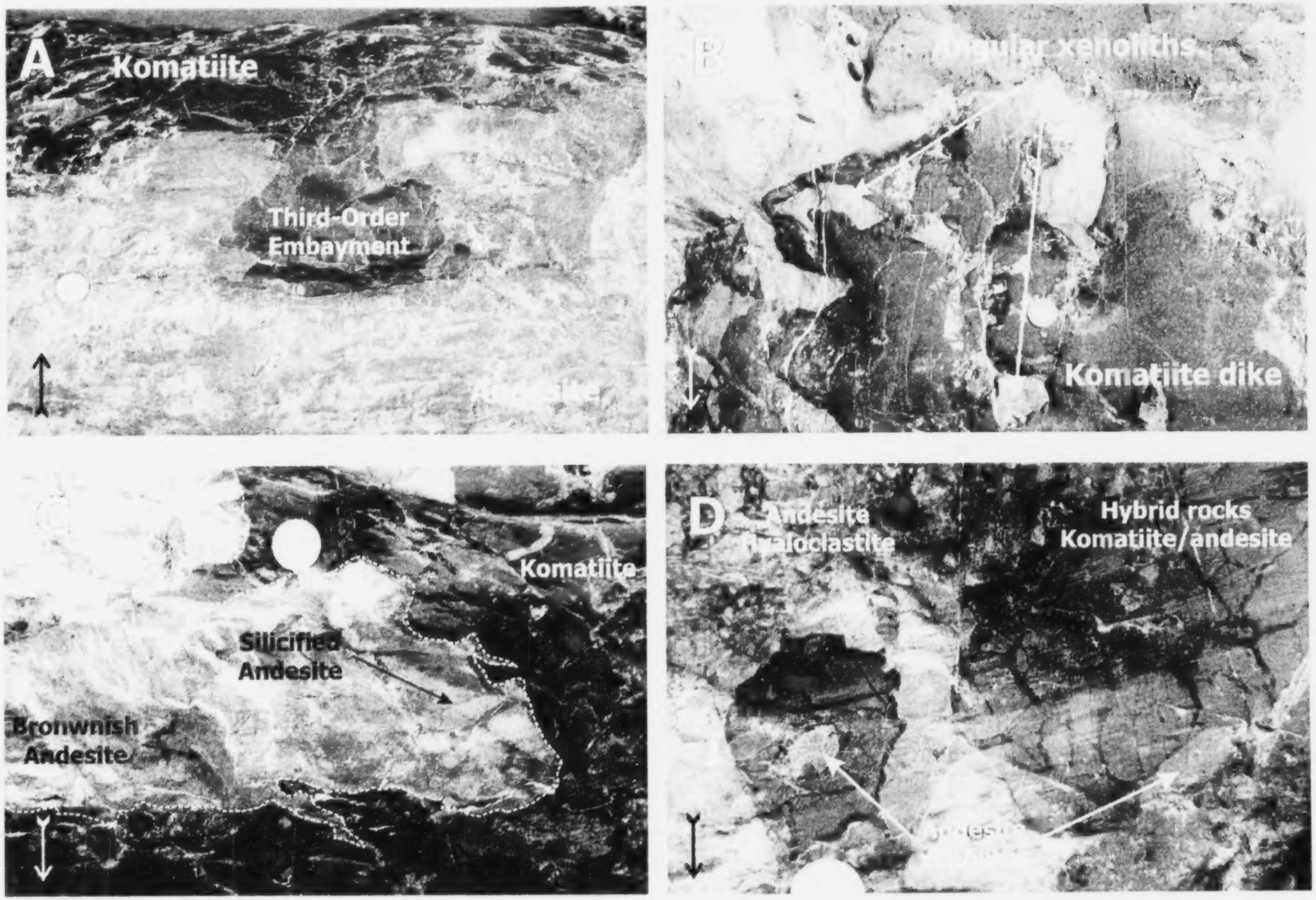
A
Komatiite
Third-Order Embayment
Andesite
B
Angular xenoliths
Komatiite dike
C
Komatiite
Silicified Andesite
Bronwnish Andesite
D
Andesite Hyaloclastite
Hybrid rocks Komatiite/andesite

Figure 7.3. A) Third-order embayment (10 to 30 cm wide, 10 to 50 cm deep) in the "East Area" at the Alexo Mine. **B)** Small angular xenoliths in a komatiitic dike in the pillowed andesitic footwall. **C)** Contact metamorphic areole along the lower contact grades from bleached and recrystallized (remelted?) andesite through recrystallized andesite. **D)** Brown (lighter grey in photo) aphyric komatiite along the footwall contact with the underlying flows, which appears to represent contamination.

- Narrow (<5 cm), irregular, aphyric komatiite dikes extend from the host unit downward into the underlying footwall rocks (Figure 7.3C). They appear to have exploited fractures, possibly generated by thermal cracking of the seawater-filled pillow andesite (N.T. Arndt, Université de Grenoble, personal communication, 2002) or by forceful intrusion (R.A.F. Cas, Monash University, personal communication, 2002), but clearly crosscut the selvages of andesite pillows.
- Small (<10 cm) angular (mechanically eroded) xenoliths (Figure 7.3B), subrounded (partially melted) xenoliths, and globular (completely melted) melted fragments of andesite occur in the komatiite near the contact and in the dikes.
- There is a continuous contact metamorphic areole along the lower contact that grades from bleached and recrystallized (melted?) andesite through recrystallized andesite (*see* Figure 7.3C), to weakly metamorphosed andesite over a distance of approximately 30 cm (*see* Figure 7.2A).
- The aphyric komatiite along the footwall contact is browner in colour than the black aphyric komatiite in the dike and in overlying flows, which appears to represent contamination (Figure 7.3D).

Together, these features provide clear evidence for both thermal and mechanical erosion. We are in the process of determining the degree of contamination in this particular komatiite, but other komatiite in the Alexo Mine sequence is characterized by $[Nb/Th]_{MN}$ ~0.8 and $[La/Sm]_{MN}$ ~0.9 compared to unmineralized komatiite in the underlying sequence, which is characterized by ($[Nb/Th]_{MN}$ ~1.3 to 1.8 and $[La/Sm]_{MN}$ = 0.5 to 0.6, providing clear evidence of *local* crustal contamination (Sproule et al. 2002).

Ore–Komatiite–Andesite Relationships at the Alexo Mine

The ores at the Alexo Mine (this study) are similar to most other komatiite-associated nickel-copper (±PGE) deposits (Lesher 1989) and to many other magmatic nickel-copper-PGE deposits (Naldrett 1989), and exhibit the following spatial and geometrical relationships between the ores, host rocks, and footwall rocks:

- Massive ores normally occur at or near the bases of the host units, which are normally the lowest, thickest, and most magnesian units in the komatiite sequence.
- The contacts between massive ores and footwall rocks are normally very sharp, but may be locally scalloped, and are normally marked by thin layers of iron-chromite; most have been tectonically modified to some degree.
- The contacts between net-textured and disseminated ores are normally very sharp, relatively planar, and marked by thin layers of iron-chromite; most have been tectonically modified to some degree.
- There is a spatial correspondence between massive and net-textured–disseminated ores: net-textured–disseminated ores normally overlie massive ores.

Many of the andesite–massive ore, massive–net-textured ore, and net-textured–disseminated ore contacts at the Alexo Mine are tectonized magmatic contacts and some are tectonically generated contacts (faults). However, some of the contacts are decorated with skeletal iron-chromites and are delicately scalloped, indicating that they are primary magmatic contacts.

The ore segregation profile at the Alexo Mine is different from many (but not all) deposits of this type in that it locally contains a thin (10 to 15 cm) layer of weakly disseminated sulphides in orthocumulate komatiitic peridotite between the net-textured and massive ore horizons (Figure 7.4). The contact between this layer and the underlying massive ore horizon is very sharp and planar, whereas the contact between this layer and the overlying net-textured ore horizon is gradational over a distance of about 5 to 10 cm.

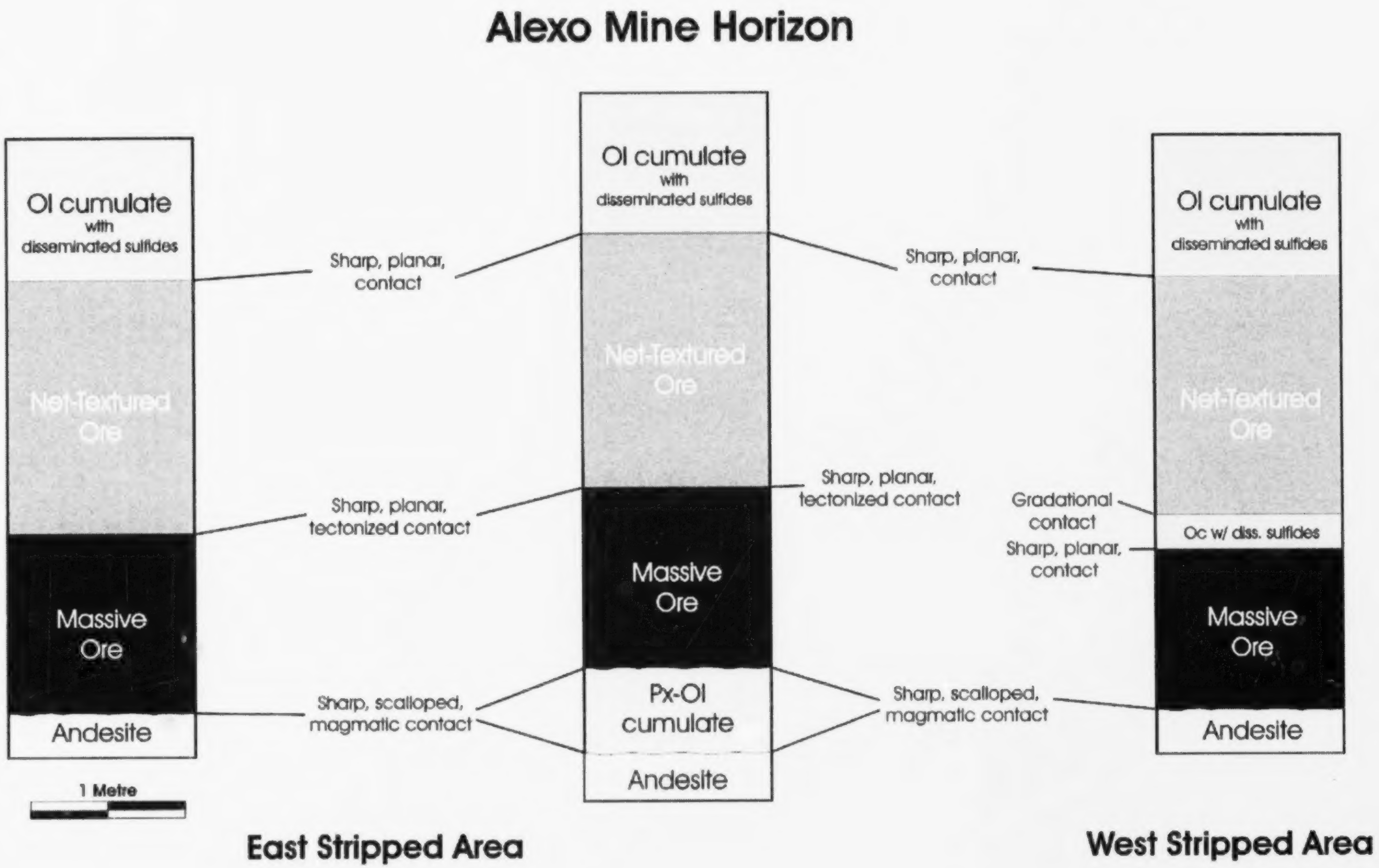
Alexo Mine Horizon
Ol cumulate
with
disseminated sulfides
Net-Textured
Ore
Massive
Ore
Andesite
Sharp, planar,
contact
Sharp, planar,
tectonized contact
Sharp, scalloped,
magmatic contact
Px-Ol
cumulate
Gradational
contact
Oc w/ diss. sulfides
Sharp, planar,
contact
1 Metre
East Stripped Area
West Stripped Area

Figure 7.4. Typical ore profiles in the new stripped areas located east and west of the old shaft at the Alexo Mine.

The massive–net-textured–disseminated ore segregation profiles in komatiite-associated nickel-copper (±PGE) deposits has been interpreted to reflect static buoyancy ("billard ball" model: Naldrett 1973), dynamic flow segregation (Hudson 1972), or dynamic remelting (Lesher and Campbell 1993). The profile at the Alexo Mine cannot be easily explained by a simple static buoyancy model and requires more a dynamic environment involving multiple episodes of ore emplacement.

Concluding Remarks

The field relationships at the Alexo Mine are similar in many respects to those reported by Groves et al. (1986), Frost and Groves (1989), Lesher (1989), Dowling, Hill and Barnes (2001), and Prendergast (2001) and are interpreted as evidence for thermomechanical erosion. The footwall contact at the Alexo Mine is more transgressive and irregular (concave to re-entrant) than the footwall contact at Kambalda, but less transgressive than the footwall contact at Perseverance or Raglan (*see* Lesher 1989), and is consistent with the thermal and fluid dynamic models by Huppert and Sparks (1985) and Williams, Kerr and Lesher (1999) suggesting that andesite should be more easily eroded than basalt, but less easily eroded than felsic volcanic rocks or sediments. These observations clearly contradict the suggestions of Cas and Beresford (2001) and Rice and Moore (2001) that komatiite should not be capable of thermal erosion.

DUNDONALD BEACH AREA

Following the recognition of the volcanic nature of ultramafic rocks in the Barberton greenstone belt by Viljoen and Viljoen (1969) and subsequent recognition in most other greenstone belts (Arndt and Nisbet 1982), the existence of ultramafic volcanic rocks is now accepted by most workers. Nevertheless, there are also numerous examples of komatiitic dikes, sills, and invasive flows (e.g., Williams 1979; Duke 1986; Arndt 1994; Davis 1997, 1999; Stone and Stone 2000; Beresford and Cas 2001; Lévesque and Lesher 2002). The Dundonald Beach area contains numerous komatiitic basalt sills and peperites (Davis 1997, 1999; Houlé et al. 2002) and is being studied as part of this project to provide insights into the mechanisms of very high-level intrusion and invasion of sediments by komatiitic magmas.

Dundonald Komatiitic Sequence

The volcanic–subvolcanic sequence in Dundonald Township comprises, from base to top (Davis 1997, 1999) 1) komatiitic flows intercalated with mafic to felsic volcanic flows; 2) a thick layered tholeiitic mafic to ultramafic sill (Dundonald Sill); 3) felsic to intermediate volcanic flows–domes containing thin komatiitic, mafic, and dacitic dikes; 4) komatiitic volcanic flows–sills intercalated with thin graphitic, sulphidic argillaceous metasediment; and 5) rare high-titanium tholeiitic basalt. The sequence is exposed in glaciated outcrops throughout the township, but the felsic to intermediate volcanic unit and upper komatiitic unit are best exposed in the Dundonald South area, which was stripped by Falconbridge Ltd. in 1989 and extended by Hucamp Mines in 2001, exposing 9000 m^2 of glacially polished outcrops known locally as "Dundonald Beach". The volcano-sedimentary package in this part of the area lies on the south-facing limb of a regional fold, strikes roughly east to west, and dips steeply to the south. The metasedimentary rocks are locally sheared subparallel to bedding, but most of the volcanic rocks and peperite are not penetratively deformed. The metamorphic grade is lower greenschist facies.

The upper komatiitic unit in the Dundonald South area comprises 3 cycles that exhibit an overall decrease in MgO content with increasing stratigraphic height, however, the MgO contents of the rocks within each cycle increase upwards (Davis 1997, 1999). Each cycle comprises 1) a lower member of thick differentiated komatiitic basalt units with lower olivine-pyroxene cumulate zones and upper acicular pyroxene spinifex-textured zones; 2) a central member of thick differentiated cumulate komatiite units with lower olivine cumulate zones and upper olivine spinifex-textured zones; and 3) an upper member of thick cumulate komatiite units with thick olivine mesocumulate to adcumulate lower zones and thin upper olivine spinifex-textured zones. The first and second cycles are exposed in the western part of Dundonald Beach (Figure 7.5). It is unclear if the eastern part of the same area (not shown) exposes the second cycle and lowermost part of the third cycle or is simply a structural repetition of the sequence exposed in the western part. The third cycle hosts most of the nickel-copper (±PGE) mineralization in the Dundonald South area, only parts of which are exposed in outcrop.

The nickel-copper (±PGE) mineralization in the Dundonald South deposit occurs as 1) stratiform contact disseminated/net-textured/massive sulphide mineralization; 2) stratabound internal disseminated, blebby, and amygdaloidal sulphide minerals; and3) minor metasediment-associated sulphide mineralization (Muir and Comba 1979; Eckstrand and Williamson 1985). The ores are hosted by (or associated with) olivine cumulate rocks that are discontinuous along strike and probably represent channelized lava flows–sills. The mineralization within the metasedimentary rocks includes both primary (peperitic) and secondary (metamorphically mobilized) types. The sulphide minerals are composed of pyrrhotite, pentlandite, chalcopyrite, millerite, electrum, and PGE alloys (Muir and Comba 1979; M.E. Fleet, University of Western Ontario, personal communication to P.C. Davis 1993). Massive ores contain, on average, about 47.5% Ni, 0.35% Cu, and 19 g/t ∑PGE (Pt+Pd+Rh+Ru+Ir+Os) in 100% sulphides, whereas disseminated ores contain, on average, about 38.1% Ni, 0.88% Cu, and 24 g/t ∑PGE (Pt+Pd+Rh+Ru+Ir+Os) (Barnes and Naldrett 1987; Davis 2001). Grab samples of massive sulphides in the first cycle at Dundonald Beach contain 20 to 34% Ni, 4.4 to 45 g/t Pt+Pd, 1.8 g/t Os+Ir+Rh, and 2.4 g/t Ru. The very high metal tenors imply very high R (mass ratio of silicate to sulphide liquid) and very reducing conditions, but the differences between ore types suggest higher R in disseminated ores than in massive ores.

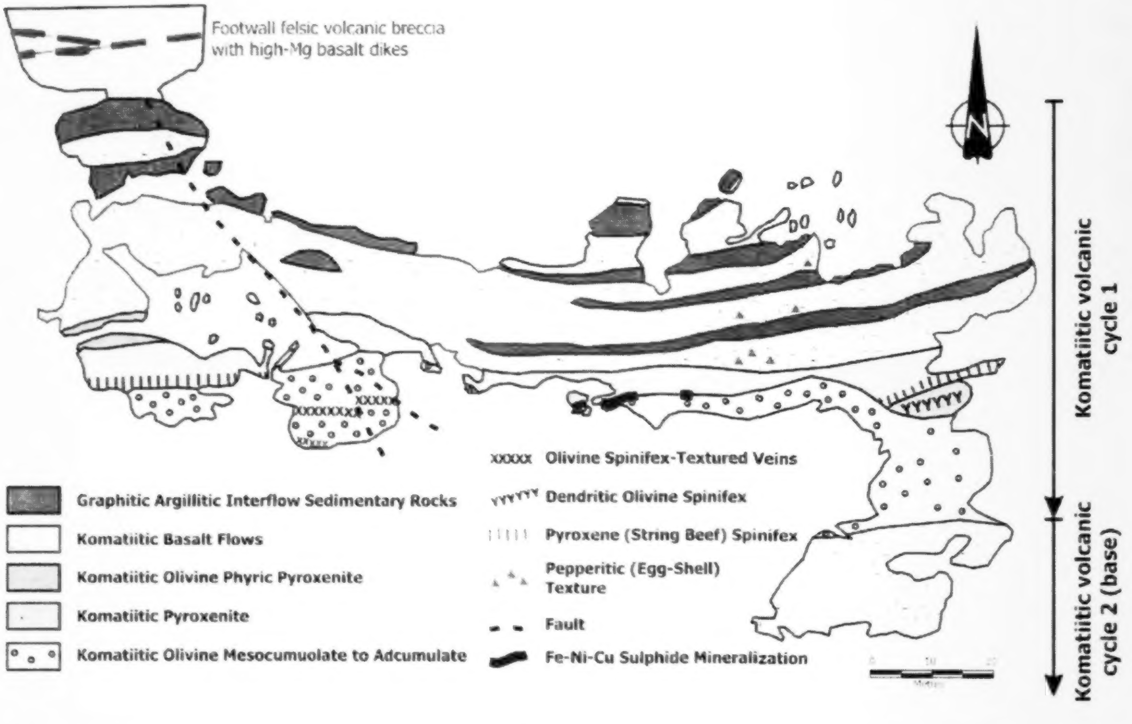
Footwall felsic volcanic breccia with high-Mg basalt dikes
N
Komatiitic volcanic cycle 1
Komatiitic volcanic cycle 2 (base)
Graphitic Argillitic Interflow Sedimentary Rocks
Komatiitic Basalt Flows
Komatiitic Olivine Phyric Pyroxenite
Komatiitic Pyroxenite
Komatiitic Olivine Mesocumuolate to Adcumulate
xxxxx Olivine Spinifex-Textured Veins
YYYYY Dendritic Olivine Spinifex
Pyroxene (String Beef) Spinifex
Pepperitic (Egg-Shell) Texture
Fault
Fe-Ni-Cu Sulphide Mineralization
0
10
20
Metres

Figure 7.5. Simplified geological map of the western part of the Dundonald Beach area (*modified from* Davis 1999). Rocks young to the south.

Intrusive and Extrusive Komatiite and Komatiitic Basalt

The komatiite and komatiitic basalt exposed at Dundonald Beach (Davis 1997) and in diamond-drill core (Muir and Comba 1979) range in thickness from 1 m to greater than 150 m and display all of the textures typical of komatiite: glassy and rubbly flow-top breccias, fine-grained random olivine spinifex textures, coarse-grained platy olivine or acicular pyroxene spinifex textures, and a wide variety of crescumulate, orthocumulate, mesocumulate, and adcumulate textures. Some of the thicker units (e.g., "Empire flow") are well differentiated with lower meso- to adcumulate zones and upper gabbroic zones, suggesting that differentiation occurred after the flow had ponded (Vicker 1991), but most of the thicker units contain an excess olivine component that accumulated prior to ponding (Davis 1997).

A large portion of the komatiitic basalt in the first cycle forms sills with thin (1 to 2 cm) symmetrical upper and lower chilled margins that crosscut previous komatiitic basalt flows and invade the graphitic argillaceous sediment, forming peperite and graphitic "egg-shell" breccia (Davis 1997, 1999). Several thin (~5-10 cm) spinifex-textured dikes occur in the underlying felsic volcanic rocks (Davis 1997, 1999). The sills may be subdivided into 2 types. Type I sills are relatively thick (~4 m), are composed of fine- to medium-grained komatiitic basalt, and have straight contacts with thin (~2 to 3 cm) very fine-grained lower and upper chilled margins. They do not appear to have interacted extensively with wall rocks. Type II sills are thinner (<50 cm), are composed of fine-grained komatiitic basalt with local globular textures (Figure 7.6B), and have wavy, irregular contacts (Figure 7.6A) with very thin (<1 cm) chilled margins. They appear to have interacted extensively with wall rocks.

Peperite is produced when hot magma intrudes unconsolidated or poorly consolidated sediment (e.g., White, Kerr and Lesher 2000). This interaction appears to have occurred between unconsolidated graphitic argillaceous sediments and the komatiitic magma in the Dundonald Beach area, producing blocky peperite, containing angular clasts of desiccated sediment in a komatiitic basaltic matrix (Figure 7.7B) and fluidal peperite, containing rounded clasts of komatiitic basalt in a metasedimentary matrix (Figure 7.7C). Peperite containing clasts of komatiite surrounded by metasediment occurs on a larger scale (metres) than peperite containing clasts of sediments surrounded by komatiite (centimetres), but both textures generally occur close to one other (Figure 7.7A).

Concluding Remarks

The volcanic–sedimentary succession at Dundonald Beach comprises (oldest to youngest): bedded rhyolitic heterolithic volcaniclastic rocks, graphitic argillaceous metasedimentary rocks, komatiitic basalt sills, differentiated komatiitic basalt flows, and poorly differentiated komatiitic peridotitic flows.

The argillite is intruded by at least 4 generations of centimetre to metre thick basaltic komatiitic sills, as established by multiphase peperite generation and crosscutting relationships between sills. The sequence of extrusive and intrusive events appears to have been 1) initial emplacement of komatiitic basalt sills into wet, unconsolidated argillite, resulting in passive fragmentation and generation of blocky peperite ranging from sediment-dominated to *in situ* komatiitic peperite; 2) continued emplacement of komatiitic basalt sills that cross-cut and engulf earlier peperite. These sills have minimal peperite along their margins, but are characterized by local finger-like injections into peperite and argillite, and flow-banded, locally spherulitic chilled margins; 3) continued emplacement of komatiitic basalt sills into argillite and earlier formed sills; 4) emplacement of low and high-magnesium spinifex-textured komatiitic flows–sills without intercalated argillite.

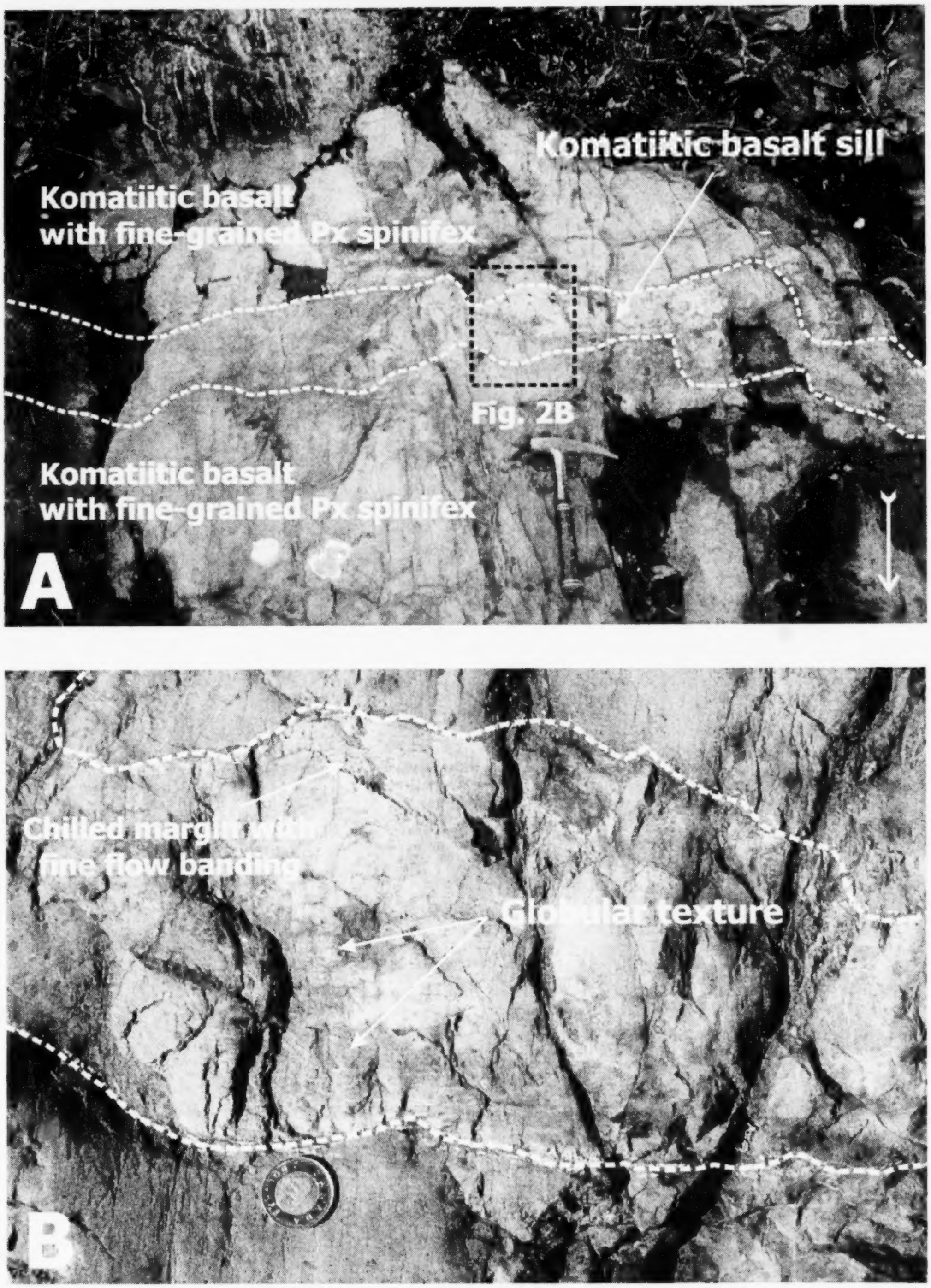
Komatiitic basalt sill
Komatiitic basalt with fine-grained Px spinifex
Fig. 2B
Komatiitic basalt with fine-grained Px spinifex
A
Chilled margin with fine flow banding
Globular texture
B

Figure 7.6. A) Type II komatiitic basalt sill showing globular textures, wavy and irregular contact with the host unit (hammer for scale). **B)** Close up of Figure 7.6A showing globular texture (coin for scale).

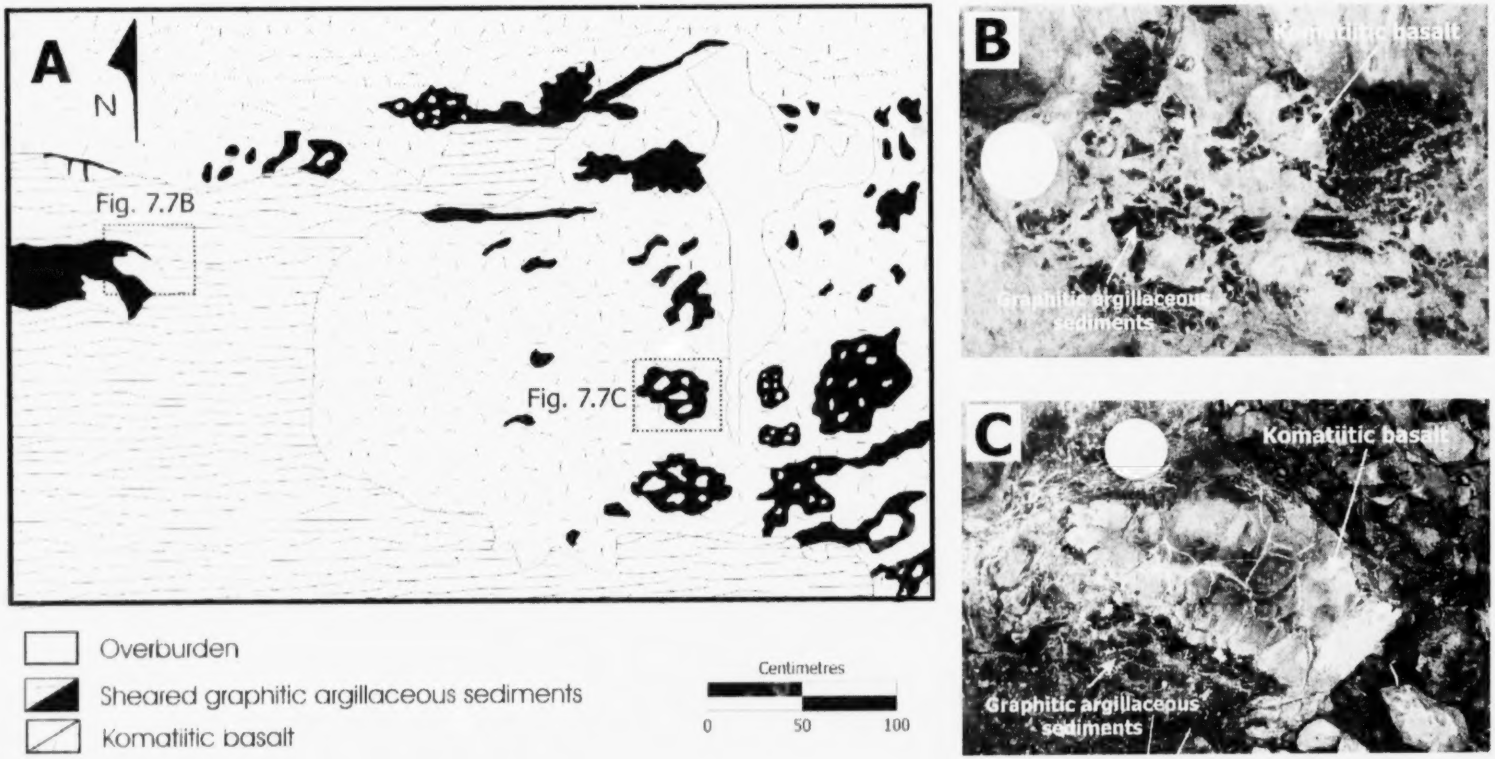
A
N
Fig. 7.7B
Fig. 7.7C
Overburden
Sheared graphitic argillaceous sediments
Komatiitic basalt
Centimetres
0
50
100
B
Komatiitic basalt
Graphitic argillaceous sediments
C
Komatiitic basalt
Graphitic argillaceous sediments

Figure 7.7. A) Detailed map showing relationship between graphitic argillaceous metasediment and komatiitic basalt at Dundonald Beach. **B)** Peperite comprising clasts of desiccated graphitic, argillaceous metasediment in a matrix of bleached komatiitic basalt. **C)** Peperite comprising clasts of bleached (contaminated?) komatiitic basalt in a matrix of graphitic, argillaceous metasediment.

The initial emplacement of sills is interpreted to have dewatered and indurated the argillaceous sediment. Peperite formation appears to have not only indurated the sediment, such that subsequent sills show minimal peperite formation and are intruded into earlier sills, sediment, and peperite, but is also interpreted to have increased the bulk density of the sediment–sill package, such that subsequent komatiitic magmas were erupted onto the seafloor. Importantly, emplacement of thin basaltic komatiitic sills did not result in assimilation of sedimentary strata or achievement of sulphide saturation. However, subsequently erupted thick, channelized pyroxenitic and peridotitic komatiitic units appear to have thermomechanically eroded sulphur-rich sedimentary rocks, achieved sulphur saturation, and segregated nickel-copper (±PGE) sulphide mineralization. The volcanic architecture of the Dundonald Beach area and abundance of high-level subvolcanic komatiitic sills suggests a proximal to near-proximal volcanic environment.

POTTER MINE AREA

The volcanic succession at the Potter Mine may be divided into 3 lithostratigraphic units: 1) a lower komatiitic sequence (LKS); 2) a middle basaltic sequence (MBS); and 3) an upper komatiitic sequence (UKS) (Figure 7.8). Previous workers (e.g., Gamble 2000) have interpreted the thick olivine adcumulate sequence west of the Centre Hill Complex to be a lava lake within the lower komatiitic sequence and the thin spinifex-textured flows at Pyke Hill to occur within the upper komatiitic sequence. However, our observations and interpretations suggest that the "Lava Lake" is stratigraphically equivalent to Pyke Hill and that sequence is folded (*see* Figure 7.8), not homoclinal.

SECTION A

Section A, studied in extensive outcrop exposures and diamond drill cores, transects all 3 lithostratigraphic units (LKS, MBS, and UKS) west of Pyke Hill (*see* Figure 7.8). Chilled margins, flow-top breccia, and asymmetric differentiation within komatiitic flow units in the LKS and UKS, together with pillow lava polarities in the MBS, indicate a stratigraphic northward-younging direction along this section.

SECTION B

Section B, studied in extensive outcrop exposures and diamond drill cores, also transects the LKS, MBS, and UKS. The "Lava Lake" area is dominated by massive to weakly-layered, medium-grained olivine adcumulate rocks that have previously been interpreted as an approximately 120 m thick lava lake that faces toward the north (Arndt 1986b). However, our studies of graded bedding, in associated volcaniclastite and thin-bedded sediment within the upper part of the MBS, and chilled margin polarities, asymmetric differentiation, vesicle orientations, fanned platy olivine spinifex, and local asymmetric contacts in spinifex horizons within the UKS, suggest that the northern part of the sequence faces northward and that the southern part of the sequence faces southward (Figure 7.9). This new structural interpretation places the "Lava Lake" at the same stratigraphic level as the thin differentiated komatiite flows exposed at Pyke Hill.

Thus, our work supports the interpretation of Oliver, Rebagliati and Haslinger (1999) that the lower komatiitic sequence, the middle basaltic sequence, and the upper komatiitic sequence at the Potter Mine represents a folded sequence rather than a homoclinal sequence.

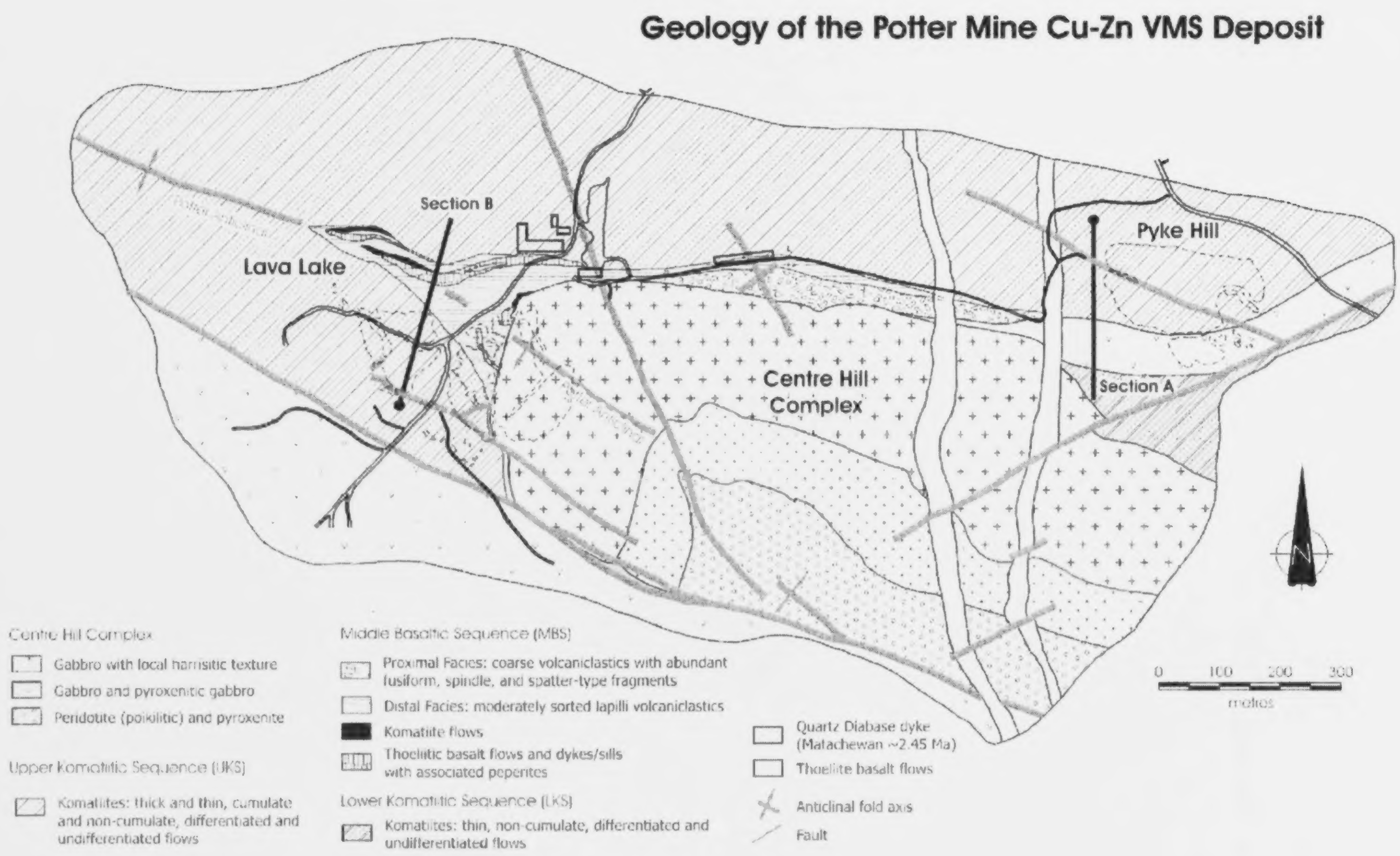
Geology of the Potter Mine Cu-Zn VMS Deposit
Lava Lake
Section B
Pyke Hill
Section A
Centre Hill Complex
N
0 100 200 300
metres
Centre Hill Complex
Gabbro with local harrisitic texture
Gabbro and pyroxenitic gabbro
Peridotite (poikilitic) and pyroxenite
Upper Komatiitic Sequence (UKS)
Komatiites: thick and thin, cumulate and non-cumulate, differentiated and undifferentiated flows
Middle Basaltic Sequence (MBS)
Proximal Facies: coarse volcaniclastics with abundant fusiform, spindle, and spatter-type fragments
Distal Facies: moderately sorted lapilli volcaniclastics
Komatiite flows
Thoeliitic basalt flows and dykes/sills with associated peperites
Lower Komatiitic Sequence (LKS)
Komatiites: thin, non-cumulate, differentiated and undifferentiated flows
Quartz Diabase dyke (Matachewan ~2.45 Ma)
Thoeliite basalt flows
Anticlinal fold axis
Fault

Figure 7.8. Geological map of the Potter Mine property (Munro Township) showing the locations of the sections of "Lava Lake" and Pyke Hill area (*adapted from* Oliver, Rebagliati and Haslinger 1999; Gamble 2000).

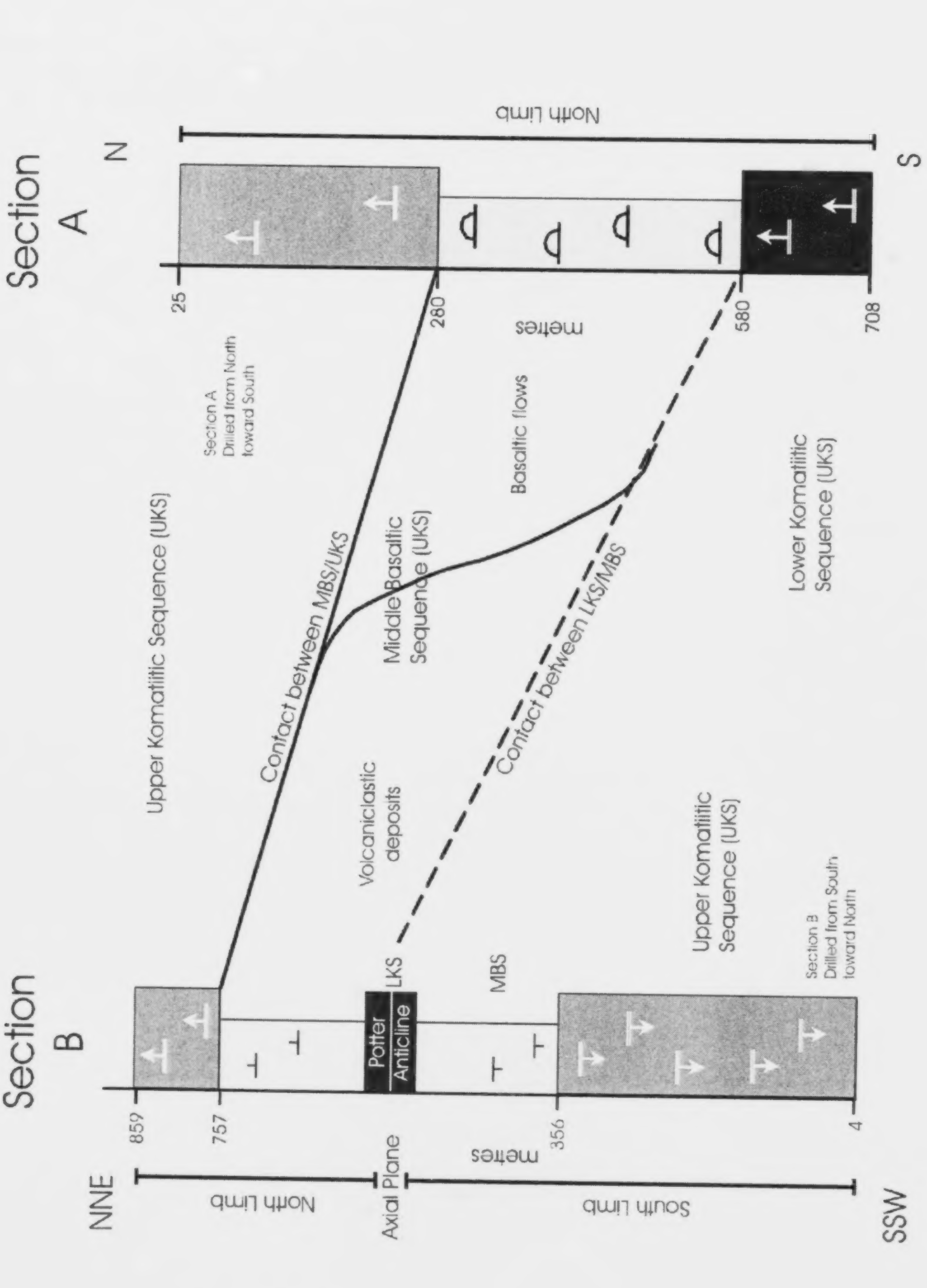
Section A
Section B
N
S
NNE
SSW
25
280
580
708
859
757
356
4
metres
metres
North Limb
North Limb
South Limb
Axial Plane
Potter Anticline
LKS
MBS
Section A Drilled from North toward South
Section B Drilled from South toward North
Upper Komatiitic Sequence (UKS)
Contact between MBS/UKS
Middle Basaltic Sequence (UKS)
Basaltic flows
Volcaniclastic deposits
Contact between LKS/MBS
Lower Komatiitic Sequence (UKS)
Upper Komatiitic Sequence (UKS)

Figure 7.9. Simplified sections at the Potter Mine property (*see* Figure 7.8). Section A contains a homoclinal sequence (LKS–MBS–UKS), whereas Section B contains a folded sequence (UKS–MBS–LKS–UKS).

Emplacement of the Komatiite Succession

Our mapping and core logging also suggests that the "Lava Lake" includes at least 6 mappable cooling units and that it may represent a series of thick sheet flows localized within a shallow depression or a series of thick sheet flows overlain by thin lava pond, rather than a single thick lava lake. Thus, it seems likely that the upper komatiitic sequence at the Potter Mine represents a compound sheet flow facies channellized by a pre-existent depression ("Lava Lake") flanked by a levée facies characterized by multiple thin undifferentiated to differentiated flows (Pyke Hill).

Concluding Remarks

The komatiite in the Potter Mine area is not known to contain nickel-copper (±PGE) mineralization, which is consistent with the paucity of lava channels and channelized sheet flows in this part of Munro Township. However, the new structural interpretation of the Potter Mine geology has important implications for volcanogenic massive sulphide exploration, as significant amounts of hydrothermal copper-zinc mineralization occurs within volcaniclastite of the middle basaltic sequence (e.g., Potter and Potter–Doal mines). Previous exploration assumed that the sequence was homoclinal rather than folded and, as a consequence, most of the drilling was targeted toward the north. The new structural interpretation opens the south limb of the Potter anticline for exploration of extensions to the Potter deposit and represent a good target for future exploration for copper-zinc volcanogenic massive sulphide mineralization (Oliver, Rebagliati and Haslinger 1999; Gibson and Gamble 2000).

FUTURE WORK

Additional work is in progress in all of these areas. Parts of the Dundonald Beach area were mapped and some of the drill cores in the area were re-logged in August to September, 2002, in collaboration with A.D. Fowler (University of Ottawa, Canada), P.C. Thurston (Laurentian University, Canada), R.A.F. Cas, S.W. Beresford, J. Trefimovs, N. Rosengren (Monash University, Australia), N.T. Arndt and Y. Lacaze (Université de Grenoble, France), and A. Gangopadhyay (University of Maryland, USA) to understand emplacement of the komatiitic volcanism in this area. Additional mapping will be done at the Alexo Mine following continued stripping by Larchex Inc. in order to better understand larger scale aspects of the channellized environment. Additional core logging will also be done in the Potter Mine area to better constrain the facies variations between "Lava Lake" and Pyke Hill.

ACKNOWLEDGMENTS

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We would like to thank Nick Arndt, John Ayer, Tony Fowler, and Phil Thurston for stimulating discussions on komatiite volcanology. We are very grateful to Paul Davis and Kevin Montgomery from MPH Consulting Ltd. (Hucamp Mines Ltd.) for their advice and assistance with the field work and core examination at the Alexo Mine and the Dundonald area; E. Bettiol, E.W. Harrison, and Dave Gamble for their advice and assistance with the field work and core examination in the Potter Mine area; and Dean Rogers and Normand Dupras (Falconbridge Ltd.) for their assistance and permission to access internal company reports.

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8. Project Unit 00-010. Geology of Cairo Township, District of Timiskaming

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INTRODUCTION

Cairo Township was mapped at a scale of 1:20 000 during the field season as a part of a multi-year project covering parts of 7 townships (Figure 8.1). The area covered approximately 100 km^2 and was mapped to improve the geological database and provide impetus for mineral exploration. The town of Matachewan is located on Highway 66 in the southwest part of Cairo Township and is approximately 60 km west of Kirkland Lake. Previous mapping by Dyer (1935) and Lovell (1967) identified the major rock types, structures and mineral occurrences, however, recognition of komatiites and the application of modern plate tectonic theory requires the re-evaluation of the area. The discovery and exploitation of gold at the Matachewan Consolidated and the Young–Davidson deposits in Powell Township, 3 km to the west, resulted in continuous exploration and discovery on new mineral occurrences throughout the area.

GENERAL GEOLOGY

Cairo Township is underlain by Neoarchean ultramafic, mafic, intermediate and felsic metavolcanic rocks, related intrusive rocks, Archean clastic and chemical metasedimentary rocks (Figure 8.2). These rocks were intruded by Archean felsic rocks of the Round Lake batholith, syenitic rocks of the Cairo stock and Paleoproterozoic diabase dikes of the Matachewan swarm. Clastic sedimentary rocks correlated with the Proterozoic Gowganda Formation of the Cobalt Group of the Huronian Supergroup unconformably overlie the Archean rocks and Paleoproterozoic dikes.

The map area covers part of the western extension of the Larder–Cadillac deformation zone. The mapping helped to delineate and characterize the many structural components of the deformation zone and related structures.

Neoarchean Rocks

Ultramafic metavolcanic rocks are present south of Highway 66 (*see* Figure 8.2). The dark green to black weathering rocks are fine grained and display spinifex, cumulate and flow breccia textures in a few locations. Pyroxene spinifex flows are generally random or radiating toward the centre of fragments or flows. Flow breccia texture is observed locally and is strongly overprinted by tectonic deformation. Peperite textures are well developed along the power line south of St. Paul Lake where pyroxene spinifex flows have incorporated sulphide-graphite-facies iron formation (*see* Figure 8.2). These textures indicate that the komatiite flowed over and partly assimilated wet sediments. Exploration for copper-nickel mineralization is highly recommended in this area.

Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.8-1 to 8-7.

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Mafic metavolcanic rocks are widespread west and south of the Cairo stock (*see* Figure 8.2). The majority of these rocks are black, extensively recrystallized and massive. Pillows, hyaloclastite and varioles were observed locally, however, these features rarely provide reliable indications of stratigraphic tops. Most mafic metavolcanic rocks display low magnetic susceptibility that helps discriminate between the diabase dikes. However, magnetite-bearing units are present locally and can be used as stratigraphic markers.

Intermediate metavolcanic flows and schist crop out mostly in the south part of the township. These rocks are light green, fine-grained and composed mostly of sericite and chlorite. White feldspar phenocrysts and porphyroblasts are common in several outcrops; chlorite-filled amygdules and vesicles are rare. The flows underlie magnetite-graphite-sulphide iron formation and appear to be interlayered with peridotite and gabbro west of Highway 65 (*see* Figure 8.2). The intense deformation and high-grade metamorphism obscures regional stratigraphic correlation.

Intermediate epiclastic rocks are more widespread than flows and are present as narrow discontinuous units interbedded with mafic metavolcanic and clastic metasedimentary rocks west and south of the Cairo stock. Epiclastic rocks generally contain subangular to angular metavolcanic clasts less than 1 cm in size in a chloritic matrix. These rocks are poorly to well sorted and locally display clast gradation.

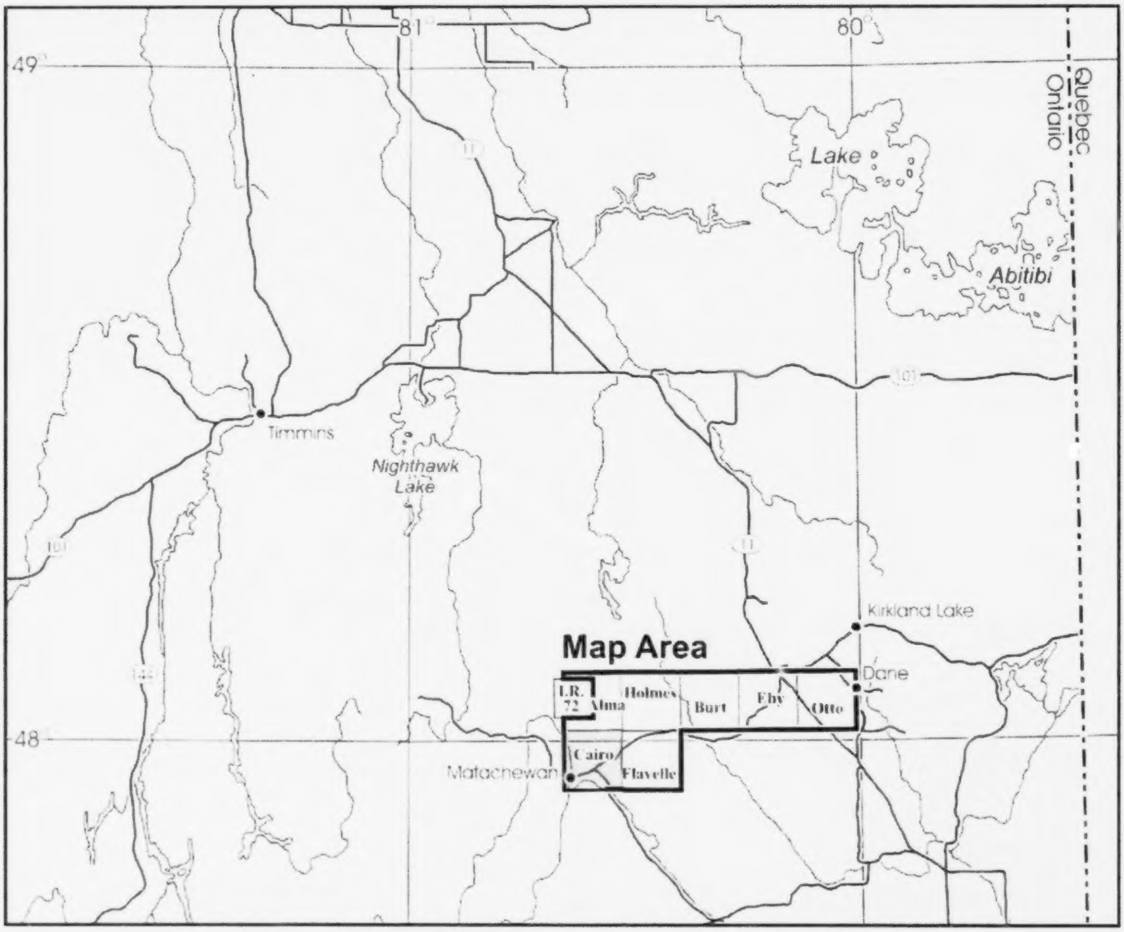

Figure 8.1. Location of the Cairo Township map area.

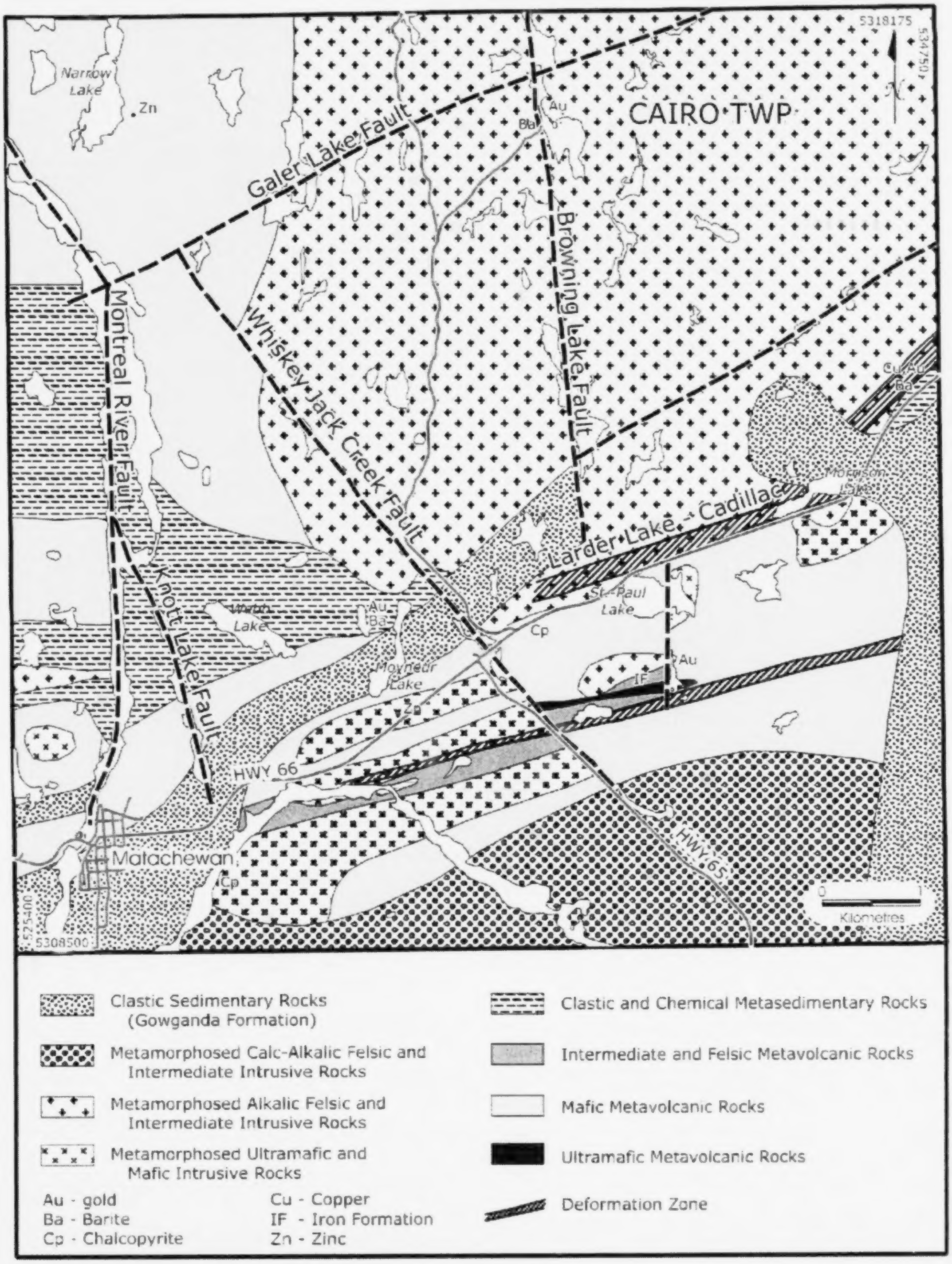
5318175
534750
Narrow Lake
Zn
Au
Ba
CAIRO TWP
Galer Lake Fault
Browning Lake Fault
Montreal River Fault
Whiskey Jack Creek Fault
Knott Lake Fault
Cu Au Ba
Morrison Lake
Larder Lake - Cadillac
St. Paul Lake
Au Ba
Cp
Au
IF
Moyneur Lake
Zn
HWY 66
HWY 65
Matachewan
Cp
0
Kilometres
525400
5308500
Clastic Sedimentary Rocks (Gowganda Formation)
Metamorphosed Calc-Alkalic Felsic and Intermediate Intrusive Rocks
Metamorphosed Alkalic Felsic and Intermediate Intrusive Rocks
Metamorphosed Ultramafic and Mafic Intrusive Rocks
Clastic and Chemical Metasedimentary Rocks
Intermediate and Felsic Metavolcanic Rocks
Mafic Metavolcanic Rocks
Ultramafic Metavolcanic Rocks
Deformation Zone
Au - gold
Ba - Barite
Cp - Chalcopyrite
Cu - Copper
IF - Iron Formation
Zn - Zinc

Figure 8.2. General geology of Cairo Township.

A felsic metavolcanic unit, composed of white to pink weathering rhyolite, was mapped on the Montreal River and Highway 66 east of Matachewan. These rocks are generally fine grained and massive with quartz and feldspar phenocrysts less than 2 mm in size. Hyaloclastic textures are recognized locally.

Conglomerate, wacke, sandstone and argillite form an arcuate unit that extends from west of the Montreal River to Webb Lake (*see* Figure 8.2). These rocks are correlated with the Timiskaming assemblage based on their quartz-rich nature, abundance of conglomerate and a detrital zircon U/Pb age of less than 2689 Ma (Ayer and Trowell 2001). Clast-supported conglomerate, containing abundant syenite boulders up to 50 cm in size, was observed along Highway 66 near the boundary with Flavelle Township. This conglomerate is also correlated with the Timiskaming assemblage. Bedding planes and primary structures are so poorly preserved in these rocks such that reliable stratigraphic indicators are rare.

Interbedded magnetite, chert, pyrite and graphite occur as a discontinuous "iron formation" unit in the south part of the map area. The unit overlies intermediate metavolcanic rocks and is locally incorporated as xenoliths in an exposure of komatiite located under the power line south of St. Paul Lake (*see* Figure 8.2). Bedded sulphide-chert iron formation occurs on Highway 66 east of Matachewan and probably represents the same unit that is observed under the power line. Airborne geophysical magnetic data indicate that the iron formation is regional in extent and may extend east to the vicinity of the former Adams iron mine south of Kirkland Lake (OGS 2000).

Intrusive rocks composed mostly of peridotite, gabbro and pyroxenite occur as sills, dikes and small plutons in the south part of the township. These intrusions are complexly folded, faulted and strongly recrystallized. Peridotite and gabbro were observed together in a few places, however, the contact between these rock types was not observed and the authors speculate that some of these intrusions may be layered. Peridotite is dark green, medium grained, massive and strongly magnetic. Serpentine, talc and magnetite are common, but asbestos fibres are rare. Primary textures are poorly preserved and it is possible that some peridotite, especially in the St. Paul Lake area, are cumulate zones of komatiitic flows. Gabbro and pyroxenite are generally dark green to black, however, leucogabbro is present locally south of the Montreal River. These rocks are medium to coarse grained, equigranular and generally weakly magnetic to nonmagnetic.

Intermediate and felsic dikes, composed of quartz-feldspar porphyry, feldspar porphyry and tonalite, intruded the metavolcanic and metasedimentary rocks throughout the map area. These dikes rarely exceed 1 m width and are discontinuous along strike. Quartz-feldspar porphyry dikes are rare and contain quartz and feldspar phenocrysts up to 3 mm in size. Feldspar porphyry contains euhedral to subhedral feldspar phenocrysts up to 1 cm in size—quartz is less than 5% of the rock. Chloritized mafic minerals constitute approximately 25 to 30% of the rock. Equigranular tonalite dikes are common and are white to pink weathering with abundant quartz and feldspar in the groundmass.

Felsic intrusive rocks of the Round Lake batholith include tonalite, quartz monzonite and granodiorite and are located along the southern boundary of Cairo and Kimberly townships. White to gray weathering foliated biotite-amphibole tonalite is the most abundant rock type and locally is gneissic with few strongly assimilated country rock xenoliths. Quartz monzonite forms a unit up to 500 m wide adjacent to the contact with the supracrustal rocks. This rock is pink to equigranular, red weathering, contains 25 to 30% chloritized amphibole and is moderately foliated. The rock is weakly magnetic and is correlative with an airborne geophysical magnetic high at the contact of the batholith (OGS 2000). Granodiorite is rare and is mixed with the quartz monzonite near the contact of the batholith.

The Cairo stock occupies most of the centre and east parts of the map area and is composed largely of syenite with minor quartz syenite and alkalic granite. Syenite is pink, red to dark red weathering and pink, red or flesh-coloured on fresh surface. All rocks are typically equigranular with grain size ranging from 3 mm to 1 cm. In many places, alignment of feldspar crystals defines a trachytic texture interpreted by the authors to be magmatic in origin. Generally, 20 to 25% of the rock is composed of bladed amphibole with minor biotite near the contacts. Magnetite up to 5% is commonly present. Quartz content locally increases from 5 to 10%, in which case the rock was mapped as quartz syenite or alkalic granite. Small xenoliths (up to 30 cm in size) of mainly mafic metavolcanic rocks locally comprise 2 to 10% of the syenite. Rare lamprophyric xenoliths and biotite-amphibole nodules similar to those observed by the author in the Otto stock, occur near the margins of the Cairo stock (Berger 2001). Quartz, barite, pyrite and fluorite veins (the largest of which is at Browning Lake) are common throughout the stock and indicate that late phase alkaline fluids pervaded fractures and faults throughout the Cairo stock.

The Cairo stock is cut by several shear zones including the Galer Lake fault and Larder–Cadillac deformation zone. Sheared syenite is commonly gray to dark red on fresh surface and pink weathering. There is pronounced grain size reduction commonly with few anhedral relict feldspar crystals and abundant growth of secondary chlorite along foliation planes. The most intensely sheared rocks contain abundant chlorite and can be mistaken for sheared mafic metavolcanic rocks especially along parts of Highway 66 near Morrison Lake (*see* Figure 8.2).

Two types of lamprophyre dikes are spatially associated with the Cairo stock. The less common type contains biotite and amphibole phenocrysts in approximately equal amounts and is light gray to slightly pink weathering. This type of dike occurs only within 250 m of the contact of the Cairo stock and is best exposed in a stripped area near Moyneur Lake. The second and more common type of lamprophyre dike contains abundant biotite with lesser amounts of amphibole and feldspar phenocrysts. These dikes are more widespread and occur up to 2 km from the Cairo stock. Dikes with this mineralogy are exposed on the west side of the Montreal River and along the south contact of the Cairo stock east of the Reserve Road (*see* Figure 8.2).

Proterozoic Rocks

Numerous diabase dikes correlated with the Paleoproterozoic Matachewan swarm cut all Archean rocks in the map area (Osmani 1991). Two types of dikes are recognized; plagioclase-phryic dikes with phenocryst abundance greater than 1% and plagioclase-aphyric dikes. The aphyric dikes commonly resemble the recrystallized mafic metavolcanic rocks, but are more consistently magnetic and less deformed than the metavolcanic rocks.

Clastic sedimentary rocks correlated with the Gowganda Formation of the Cobalt Group of the Proterozoic Huronian Supergroup unconformably overlie all Archean rocks (Lovell 1967). Conglomerate, sandstone, wacke, siltstone and argillite up to 90 m thick occur mainly along the inferred trace of the Larder – Cadillac deformation zone and in the southeast part of the township. Conglomerate along Highway 66 contains granitic boulders up to 70 cm in diameter, however, other clasts consist of mafic and felsic volcanic rocks, gneissic rocks, dioritic rocks, metasedimentary rocks and rare chert. Red to white weathering lithic sandstone and arkose are most abundant and rarely thin beds and laminae rich in detrital magnetite occur near the unconformity in these rock types. Siltstone and argillite comprise thin units (up to 15 cm thick) and are interbedded with the sandstone and arkose.

STRUCTURE AND METAMORPHISM

The map area is structurally complex with evidence for Archean, Proterozoic and Paleozoic deformation.

Archean deformation is characterized by multiple phases of shearing, faulting and folding. A prominent 50 to 100 m wide shear zone exposed along Highway 66 may represent the western extension of the Larder–Cadillac deformation zone. Several areas stripped by various exploration companies show that a S_1 foliation commonly filled with quartz veins is folded and transposed by an axial planar east-northeast-striking foliation (S_2) with steep north and south dips. Shallow plunging lineations combined with dextral offset of rock units and earlier fabrics by S_2 faults indicate that late movement was largely transcurrent. Several parallel shear zones and faults, including the Galer Lake fault, also display dextral movement of the S_2 foliation. F_2 folding with an axial planar foliation in the south part of Cairo Township, is indicated by repetition of peridotite and gabbro units that correspond to map-scale folds on regional airborne magnetic data (OGS 2000).

A narrow (25 to 30 m) easterly striking shear zone exposed on Highway 65, displays south-side up reverse movement and indicates that other generations of shear zones occur in the map area. This zone is approximately 1 km north of the contact with the Round Lake batholith and may reflect movement related to intrusion of the batholith.

Proterozoic deformation is characterized by penetrative foliation in parts of the Gowganda Formation that overlie the major Archean shear zones and is inferred to result from reactivation of Archean structures during the Proterozoic (Powell and Hodgson 1992). Numerous north-striking faults, that include the Montreal River, Whiskey Jack Creek and Browning Lake faults, disrupt Archean and Proterozoic rocks and are characterized by brittle fault gouge (*see* Figure 8.2). Lovell (1967) and Lovell and Caine (1970) inferred that these faults experienced reactivation during formation of the Timiskaming rift in the Paleozoic.

The area is characterized by upper greenschist-facies to lower amphibolite-facies metamorphism with higher metamorphism adjacent to the Cairo stock and the Round Lake batholith. The metamorphism, combined with the locally intense structural deformation, has resulted in extensive recrystallization of the supracrustal rocks and widespread destruction of primary textures. A distinctive calc-silicate mineral assemblage characterized by abundant epidote, chlorite and commonly calcite occurs as thick veins or pervasive alteration in calcium- and magnesium-rich protoliths, such as the ultramafic metavolcanic and intrusive rocks and the intermediate metavolcanic rocks. Calc-silicate veining accompanies some sphalerite-bearing veins and gold-bearing metasedimentary rocks southwest of the Cairo stock and may represent prograde metamorphism of an earlier hydrothermal alteration in these areas.

MINERALIZATION

Gold and silver were extracted from the Consolidated Matachewan and Young–Davidson mines approximately 3 km west of Cairo Township between 1934 and 1957 (Lovell 1967). Gold exploration continues throughout the map area with mineralization discovered in 2 major environments. Gold accompanied by pyrite, chalcopyrite and, less commonly, fluorite, sphalerite and galena occurs in quartz veins that cut the Cairo stock and supracrustal rocks. These veins are typically narrow (less than or equal to 1 m wide), discontinuous and are aligned along the S_2 foliation or along the north-striking faults. Gold also occurs in sulphide-bearing haloes at the edges of some of these veins. Gold accompanied by disseminated and stringer pyrite and chalcopyrite occurs along the southern contact of the Cairo stock near the boundary with Flavelle Township (*see* Figure 8.2). The mineralization is accompanied by tourmaline, barite, fluorite and altered feldspar, suggesting a porphyry gold-copper style of mineralization.

Barite commonly accompanied by fluorite and quartz occurs in veins within and around the periphery of the Cairo stock. The authors attribute this style of mineralization to oxidized hydrothermal fluids associated with late phase crystallization in the stock. Bulk sampling and metallurgical tests of the Browning Lake vein produced a concentrate of 91% barite, which is considered insufficient for commercial purposes (R. Hill, President, Extender Minerals Inc, personal communication, 2001). However, several barium geochemical anomalies and barite in till targets were identified by Bajc (1997) and by Inco Exploration and Technical Services Limited (Kirkland Lake Resident Geologist's Office, assessment file KL-3176). More commercial mineralization may be present in the area.

Spinifex-textured komatiite flows occur in contact with sulphide-graphite-facies iron formation along the power line in south Cairo Township (*see* Figure 8.2). Peperite textures developed in the komatiite indicate that the flows were extruded onto wet sediments. There exists the potential for komatiitic-hosted copper-nickel mineralization in this setting.

Zinc mineralization is present in interflow metasedimentary rocks in northwest Cairo Township, indicating the potential for base metals in this area. Chalcopyrite-bearing quartz stringers hosted in quartz monzonite and tonalite are present south of the Montreal River and, in the authors' opinion, has not been explored to its full potential.

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9. Are the Neoarchean Diamond-Bearing Breccias in the Wawa Area Related to Late-Orogenic Alkalic and "Sanukitoid" Intrusions?

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INTRODUCTION

The Michipicoten greenstone belt at Wawa has been the focus of exploration activity for diamonds discovered in Archean mica- and actinolite-rich heterolithic breccias and associated lamprophyre dikes (Atkinson et al. 2002; Figure 9.1). The heterolithic breccias typically possess an ultramafic matrix. These metamorphosed and tectonically deformed rocks have presented an interesting puzzle and have been reported to include diamondiferous volcaniclastic units by several exploration companies working in the area (Atkinson et al. 2002). Few age determinations have been reported for these rocks; an age of 2674±8 Ma for titanite in a lamprophyre dike (R.P. Sage, Ontario Geological Survey, unpublished data, 2000) was obtained from a sample collected by R.P. Sage, Ontario Geological Survey, from the GQ discovery site held by Band-Ore Resources Limited in Musquash Township. This compares with the age of 2673±8 Ma for the syenitic Dickenson Lake stock (Turek, Sage and Van Schmus 1990; Sage 1993).

The purpose of this note is to bring attention to some observations we made on structural and lithologic relationships across several exploration properties in Musquash, Menzies and Lalibert townships and to speculate on the petrogenesis of these heterolithic breccias and lamprophyre dikes and their diamonds.

OBSERVATIONS

Breccia dikes were observed in Musquash Township at several bedrock exposures along the Musquash Township road: at the GQ property of Band-Ore Resources Limited, the Barnett Lake zone, and the Engagement zone. These rocks are rich in mica and consequently alkalic in composition. Altered amphibole phenocrysts occur widely. In each location, the mica-actinolite-rich rocks contain either ultramafic clasts or varying concentrations of heterolithic fragments ranging in composition from mafic and felsic metavolcanic to ultramafic rocks and minor granite and tonalite gneiss. The clasts within heterolithic breccias, which are locally closely (genetically?) associated with these dikes, are concentrated in bands and resemble volcaniclastic debris flow units. However, in the Enigma property held by Arctic Star Diamond Corp. in Menzies and Lalibert townships, the heterolithic breccia units appear to transect the surrounding volcanic rocks, including dacitic lapilli tuff and pillowed basalt. The ultramafic intrusions and associated breccias generally vary in width from several centimetres to several tens of metres. Breccia or inclusion-bearing dikes appear to have experienced several episodes of intrusive activity resulting in crosscutting dikes; dikes that appear to be slightly younger than, but almost coeval with, the breccias; and dikes with complex intrusive relationships in syenite near the Dickenson Lake stock (Photos 9.1 and 9.2).

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.9-1 to 9-10.

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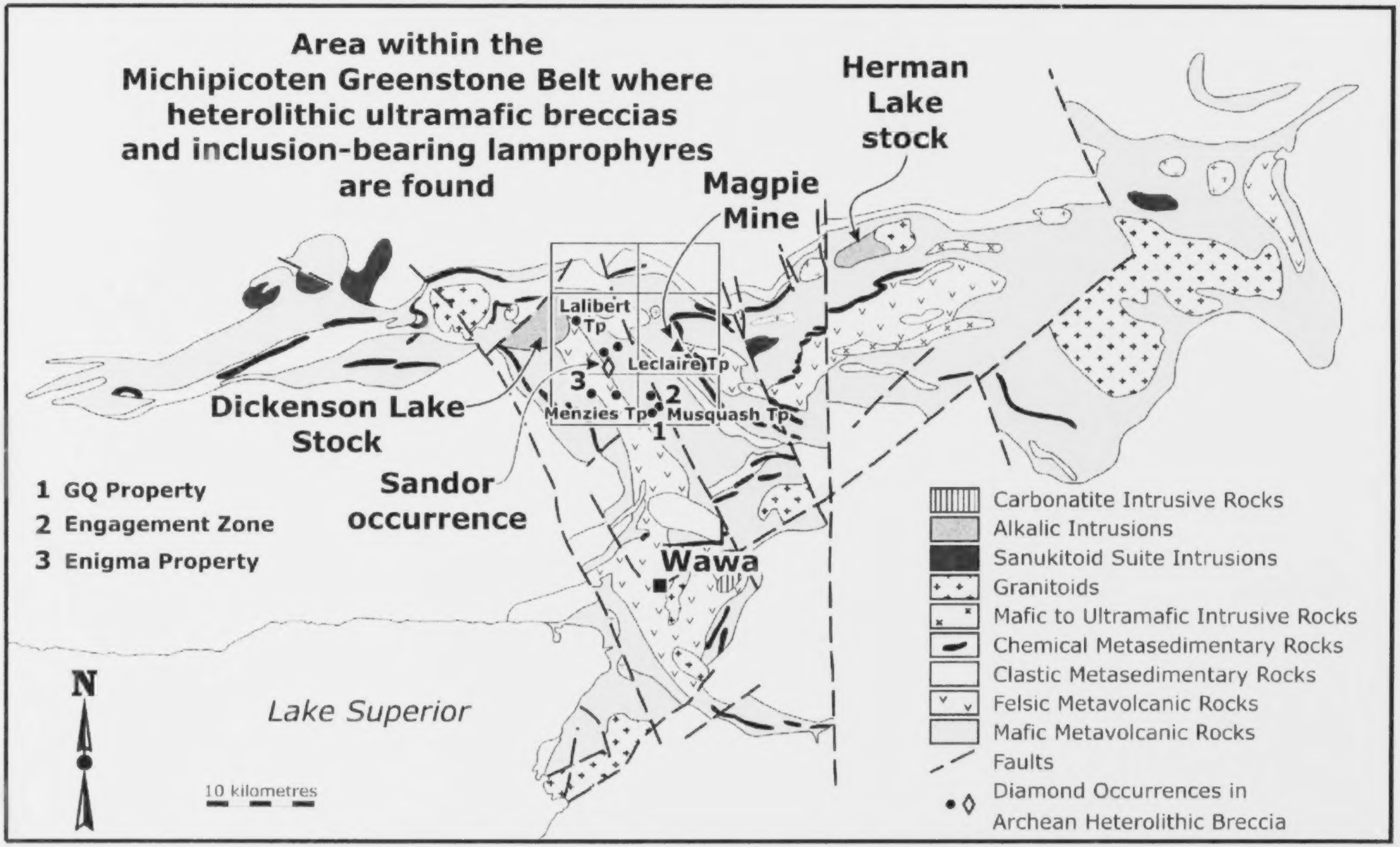
Area within the Michipicoten Greenstone Belt where heterolithic ultramafic breccias and inclusion-bearing lamprophyres are found
Herman Lake stock
Magpie Mine
Lalibert Tp
Leclaire Tp
Menzies Tp
Musquash Tp
1
2
3
Dickenson Lake Stock
Sandor occurrence
Wawa
Lake Superior
N
10 kilometres
1 GQ Property
2 Engagement Zone
3 Enigma Property
Carbonatite Intrusive Rocks
Alkalic Intrusions
Sanukitoid Suite Intrusions
Granitoids
Mafic to Ultramafic Intrusive Rocks
Chemical Metasedimentary Rocks
Clastic Metasedimentary Rocks
Felsic Metavolcanic Rocks
Mafic Metavolcanic Rocks
Faults
Diamond Occurrences in Archean Heterolithic Breccia

Figure 9.1. The Michipicoten greenstone belt showing locations of inclusion-bearing breccia dikes, some of which contain diamonds. Alkalic- and sanukitoid-suite plutonic bodies are shown along the northern part of the greenstone belt. (*Modified after* Sage 1999).

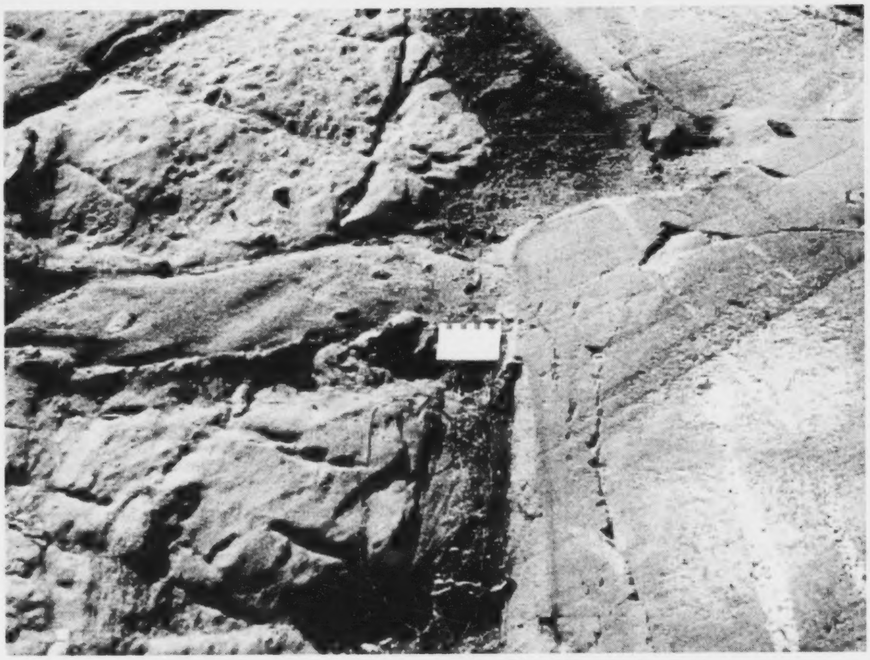

Photo 9.1. Heterolithic breccia with abundant syenitic and ultramafic inclusions containing lamprophyric dike (centre-left) intersected by a boudinaged, lamprophyric dike (right side) containing large ultramafic xenoliths. Outcrop on a road south of McCormick Lake, Lalibert Township.

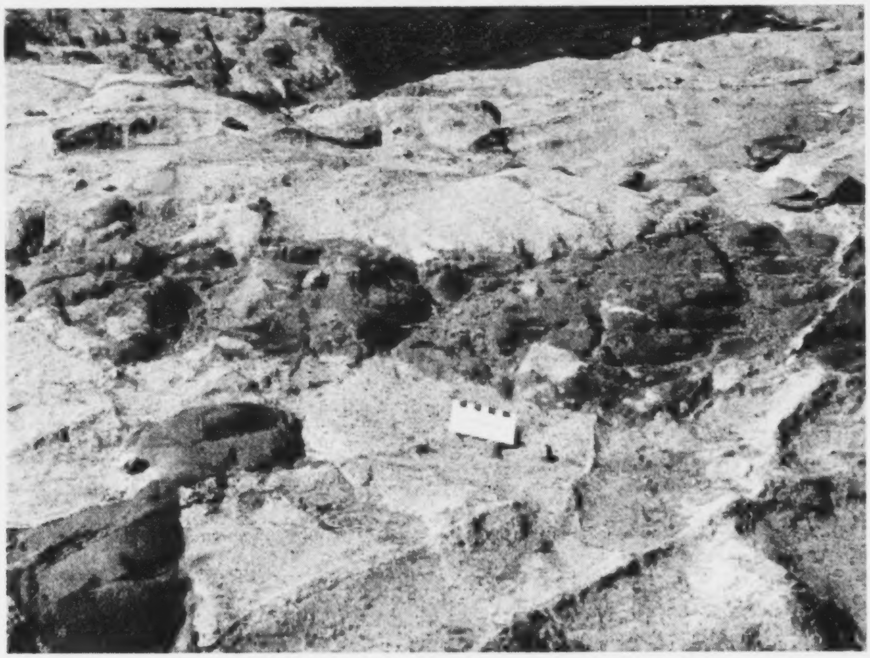

Photo 9.2. Heterolithic breccia dike with ultramafic mica-amphibole-rich matrix cutting syenite that contains ultramafic inclusions. Clasts of syenite occur within the dike and, in places, the dike shows various degrees of dismemberment within the syenitic host, typical of ductile magma mingling of coeval intrusive units. *See* Photo 9.4 for a different view of the same intrusion.

Northeast of the GQ property, one can observe reopened or reactivated dikes resulting in a complex of monolithic, typically ultramafic dikes with ultramafic clasts intruding the heterolithic breccias, which intrude metavolcanic host rocks. The breccia clasts are concentrated into tabular bands within some dikes.

A broad ultramafic intrusion, containing heterolithic breccia locally concentrated in bands, is exposed at the Engagement zone. The breccia fragments are subrounded to angular. The intrusive nature of this rock is most apparent where it sharply transects the metavolcanic host rocks and has locally brecciated units of pillowed basalt into large block-like, fragments several metres in diameter. Based on these types of contact relationships, the authors suspect that heterolithic units are flow-concentrated, diatreme-like breccias that grade into more massive portions.

A foliation, parallel to the dike walls, is interpreted to be defined by a planar preferred alignment of minerals that was developed during emplacement of the dikes (although the rocks have subsequently been metamorphosed). This foliation is oriented at an oblique angle to, and overprinted by, a regional flattening foliation that affects the surrounding metavolcanic rocks. At the Enigma property (*see* Figure 9.1),

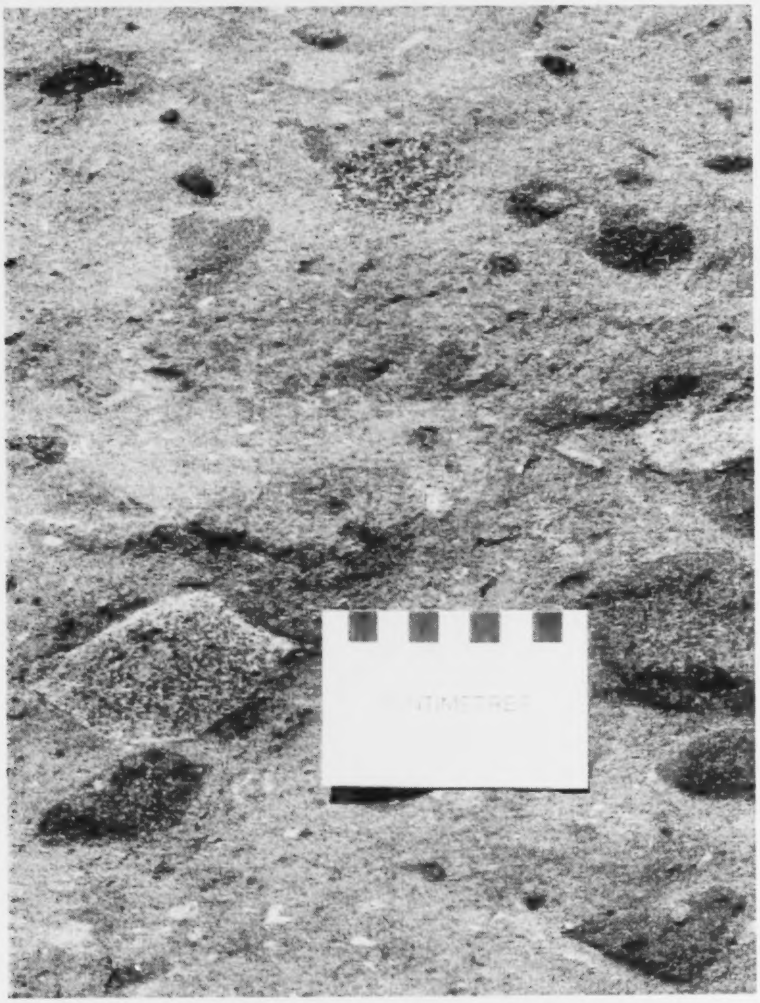

Photo 9.3. Heterolithic breccia with mica-amphibole-rich matrix and diverse clasts ranging from ultramafic to syenitic; south of McCormick Lake, Lalibert Township.

features of the heterolithic breccias include a close temporal relationship to grey syenite intrusions, which the authors interpret to be associated with the late orogenic (circa 2673 Ma) alkalic intrusive event (Sage 1994) represented by the Dickenson Lake stock. South of McCormick Lake in Lalibert Township, the heterolithic breccia contains a large number of syenitic clasts (Photo 9.3), some of which appear to form a train of clasts that resemble a dismembered dike, similar in composition to the adjacent syenite pluton. The syenite is overprinted by a regional flattening foliation and pronounced mineral lineation, similar to fabrics observed in all other rock units, including the heterolithic breccias and lamprophyre dikes. There is evidence, in outcrops, that the heterolithic breccia locally intrudes the syenite breccia and is, in turn, intruded by syenite dikes containing ultramafic fragments. In one example, a syenite dike is dismembered within the heterolithic breccia unit. In another example, a heterolithic breccia intrudes the syenite. An apophyse of the heterolithic breccia is also brecciated within the syenite (Photo 9.4).

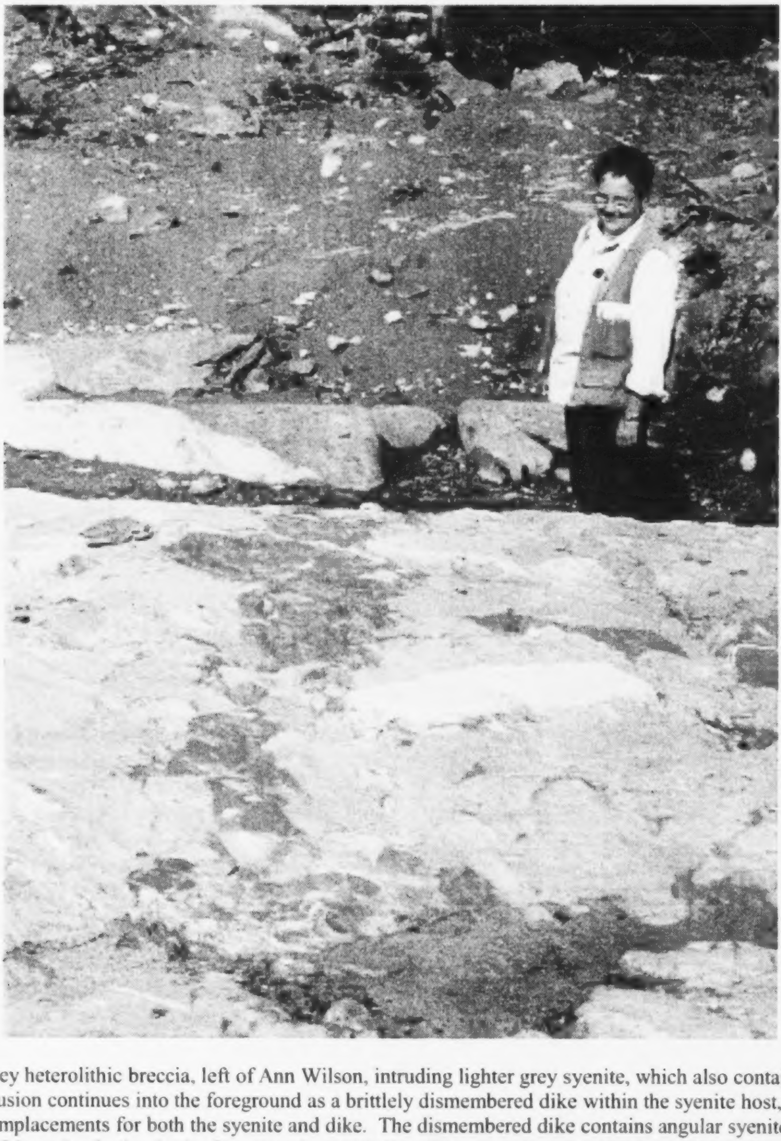

Photo 9.4. Dark grey heterolithic breccia, left of Ann Wilson, intruding lighter grey syenite, which also contains heterolithic clasts. Breccia intrusion continues into the foreground as a brittlely dismembered dike within the syenite host, typical of closely contemporaneous emplacements for both the syenite and dike. The dismembered dike contains angular syenite inclusions (*see* Photo 9.2) and itself degrades further in the foreground, outside the photo view, into a train of inclusions. Outcrop on a road south of McCormick Lake, Lalibert Township.

Recent Archean diamond discoveries in the Abitibi greenstone belt, south of Cobalt, which were discovered following recommendations by G.P.B. Grabowski in Meyer et al. (2001), exhibit similar relationships to those described above at Wawa. At the Gossan property, centred in Lot 6, Concession 3, Lorrain Township, diamondiferous lamprophyre dikes with felsic to ultramafic metavolcanic and granitic xenoliths intrude pillowed mafic metavolcanic rocks. Locally, these dikes are closely associated with diamond-bearing heterolithic breccias that include felsic to mafic metavolcanic, granitic and lamprophyric clasts in an ultramafic matrix (Photo 9.5). The lamprophyre dikes occur within the breccias, but locally display relationships suggesting coeval development. These include contact relationships in which the dikes appear to merge and coalesce with the heterolithic breccias (Photo 9.6) rather than crosscut them with sharp intrusive contacts. A possible similar intrusive complex, at the southern margin of South Lorrain Township, was described by Todd (1925) as containing heterolithic breccia. This suggests that the area of investigation should be expanded south of Cobalt.

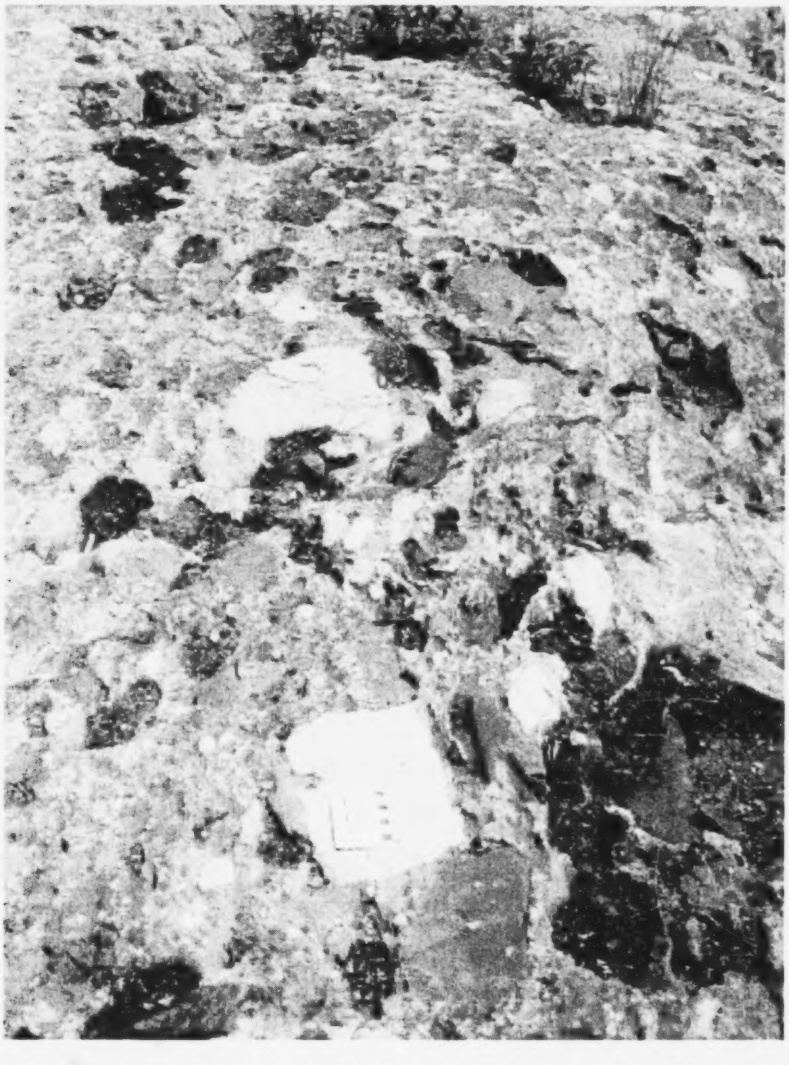

Photo 9.5. Diamond-bearing heterolithic breccias that include felsic to mafic metavolcanic, granitic and lamprophyric clasts in an ultramafic matrix. Location is south of Cobalt, Abitibi greenstone belt, in Lorrain Township, Lot 6, Concession 3.

These relationships are observed in co-magmatic ultramafic to felsic phases of late orogenic, typically alkalic intrusions (>5 weight % alkalis for SiO_2 = 55 to 60 weight %) where complex magma mingling has occurred. Such observations have been made, for example, in the margin of late orogenic intrusions of the Onaman–Tashota terrane in eastern Wabigoon Subprovince (G.M. Stott, Ontario Geological Survey, unpublished data, 1999). Late orogenic, mantle-derived, syenite, monzonite and monzodiorite intrusions (assigned by Stern, Hanson and Shirey (1989) to the "sanukitoid" suite) have been recognized in the Shebandowan greenstone belt west of Thunder Bay. The origin of these kinds of rocks, the undersaturated ultrapotassic plutons and accompanying ultramafic components, which postdate terrane collisions, has been attributed to the partial melting of a metasomatized mantle wedge under an arc, heterogeneously enriched in incompatible elements by interaction with a melting slab during subduction (e.g., Sajona et al. 2000; Stern, Hanson and Shirey 1989; Mitchell 1996).

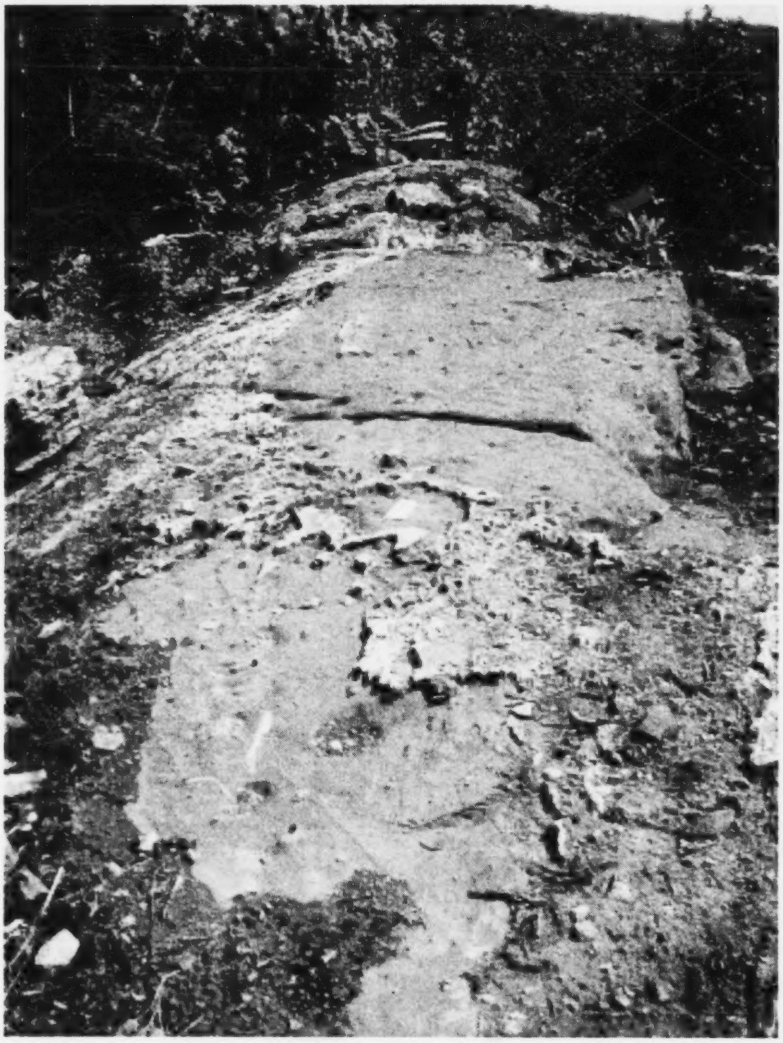

Photo 9.6. Lamprophyre dike within heterolithic breccia and locally appearing to merge and coalesce with the breccia, suggesting coeval development. Location is south of Cobalt, Abitibi greenstone belt, in Lorrain Township, Lot 6, Concession 3.

Many late tectonic alkalic intrusions, dominated by those that postdate the regional tectonic flattening fabric, contain ultramafic phases, such as those documented in the northern part of the Quetico Subprovince by Lassen, Hattori and Percival (2001). In the Michipicoten greenstone belt, however, syenitic intrusions, such as the Dickenson Lake stock, are syntectonic and intrusive phases temporally associated with this magmatic event are affected by the regional folding and flattening foliation. It is conceivable that the greater extent of heterolithic breccia, associated with the alkalic intrusions in the Michipicoten belt is a consequence of the syntectonic timing of magma emplacement, allowing the magma to be concentrated with long axes parallel to the regional foliation and folding. Much of the felsic component of the magmatism occurs only as small "windows" (including the Dickenson Lake stock) at the current crustal level of erosion.

A SUGGESTION WITH BROAD IMPLICATIONS

The authors suggest or postulate, from the combination of observations at all of the properties that were visited, that the diamond-bearing lamprophyre dikes and heterolithic breccias (e.g., Atkinson et al. 2002) are related to a late orogenic alkalic suite of intrusions that were emplaced approximately 2673 million years ago during the Kenoran Orogeny (the regional crustal-shortening event). However, due to a relative lack of information, this area will require detailed bedrock mapping, structural studies, lithogeochemistry and geochronology to evaluate this suggestion.

The implications are far ranging since late orogenic, mantle-derived intrusions have been observed to occur widely across the Superior Province, especially near subprovince boundaries and major crustal faults. These intrusions were generally intruded after 2690 Ma in the Wawa Subprovince (e.g., Corfu and Stott 1998) and reflect a widely observed temporal change in the nature of plutons toward more alkalic compositions during and subsequent to the Kenoran Orogeny (e.g., Card 1990).

TENTATIVE CONCLUSIONS AND RECOMMENDATIONS

There are two fundamental requirements to bring diamonds to the Earth's present surface: a deep magmatic transport mechanism for scavenging diamonds from the mantle and a structural control to provide a pathway for diamond-bearing magmas. Neither of these requirements is fully understood in the Wawa area. There is some structural and lithologic evidence to suggest that the diamond-bearing heterolithic breccias, and their more massive to strongly foliated portions, are late tectonic intrusions that overlap in time with the formation of late orogenic alkalic intrusions, such as the Dickenson Lake stock, which was intruded circa 2673 Ma. This implies that these breccia units, typically with an ultramafic matrix and containing either heterolithic clasts or monolithic ultramafic clasts, are coeval and likely co-magmatic with Neoarchean alkalic and possibly sanukitoid intrusions that formed late in the dominant period of crustal shortening during the Wawan phase of the Kenoran Orogeny (cf. Stott 1997).

The authors suggest that an exploration model for similar diamond-bearing, heterolithic breccias should accommodate the possibility that these rocks are late orogenic and appear to be emplaced coeval with alkalic intrusions, notably the Dickenson Lake diorite-nepheline syenite stock and possibly the suite of sanukitoid intrusions along the northern part of the Michipicoten belt (Sage 1994; Santaguida 2001). We suggest assessing these heterolithic breccias as late orogenic diatreme breccias associated with alkalic intrusions emplaced at the same time as several more prominently mapped felsic sanukitoid intrusions across the northern part of the belt. On a broader scale, encompassing the Superior Province, we suggest that volumetrically significant heterolithic breccias and lamprophyric phases associated with other late orogenic alkalic, and possibly sanukitoid intrusions, should be investigated for their diamond potential.

Previously, the ultramafic phases of such late intrusions, which have attracted some attention for their platinum group element potential in northwestern and northeastern Ontario, have not been suggested as possible carriers of diamonds from the mantle. Accordingly, exploration should be conducted on ultramafic intrusions, breccias and lamprophyre dikes in the vicinity of other Archean alkalic plutons in Ontario (Sage 1991), such as the Sturgeon Narrows alkalic complex (Trowell 1976, 1983) and the Bell Lake stock (Trowell 1983) in the Sturgeon Lake area of the western Wabigoon Subprovince; the Falcon Island stock on Lake of the Woods (Ayer 1991, 1998); an intrusion west of the Falcon Island stock (Morris 1988); and in the vicinity of heterolithic breccia intrusions recorded elsewhere, such as on the south edge of South Lorrain Township (Todd 1925), southwest of Lake Timiskaming.

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10. Project Unit 99-001. Precambrian Geology of the Dinorwic Area, Wabigoon Subprovince

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INTRODUCTION

This contribution summarizes observations and preliminary interpretations based on work carried out during the previous summer. This work forms part of a multi-year investigation of the geology of the Wabigoon–Dinorwic Lakes area (Beakhouse 2000, 2001) which was last mapped by J. Satterly in 1941 (Satterly 1943). The area investigated during the 2002 field season encompasses Southworth Township as well as some unsurveyed area to the west.

REGIONAL SETTING

The Wabigoon–Dinorwic area is transected by the Wabigoon fault, which is a major regional structure that separates 2 geologically distinct domains within the Wabigoon Subprovince. Distinct mineral deposit types and styles also characterize these domains.

The Sioux Lookout domain, lying to the north of the Wabigoon fault, is characterized by a series of alternating sedimentary-dominated and volcanic-dominated panels that consistently face to the south. Many of these panels are regionally interpreted to have fault contacts, however, some of the contacts appear to be conformable depositional contacts with minimal superimposed strain. This area has a complex deformational history with an early, generally bedding-parallel fabric (D_1) deformed into a series of megascopic to regional-scale, southwest-plunging, Z-asymmetric folds with the development of a second fabric (D_2) parallel to the axial surface of these folds. Metamorphic grade varies regionally from upper greenschist facies to upper amphibolite facies, with the lowest grade generally occurring nearest to the Wabigoon fault. Gold deposit types in this area include disseminated and vein type mineralization. Rare-element pegmatites, associated with the Ghost Lake batholith, occur primarily within the Brownridge volcanics, although relatively evolved pegmatites have also been found within the Brownridge sediments to the east of Ghost Lake. Base metal sulphide mineralization is not common, although several sulphide mineral occurrences, and possibly related synvolcanic alteration, occur near the stratigraphic top of the Brownridge volcanics.

The Atikwa domain occurs to the south of the Wabigoon fault and is characterized by dominantly volcanic sequences that face away from large, coeval batholiths (e.g., Atikwa Batholith, Aulneau Batholith). Within the map area, the Wabigoon metavolcanics are typical of these sequences with a thick basal portion consisting almost entirely of mafic metavolcanic rocks overlain by a more heterolithic portion, which, although still dominantly mafic metavolcanic, includes minor intermediate to felsic metavolcanic rocks and rare metasedimentary rocks. South of Wabigoon Lake, the structure is relatively simple with a northward-facing homoclinal sequence characterized by generally weak fabric development except in close proximity to the Wabigoon fault. Mineral assemblages indicative of regional middle to

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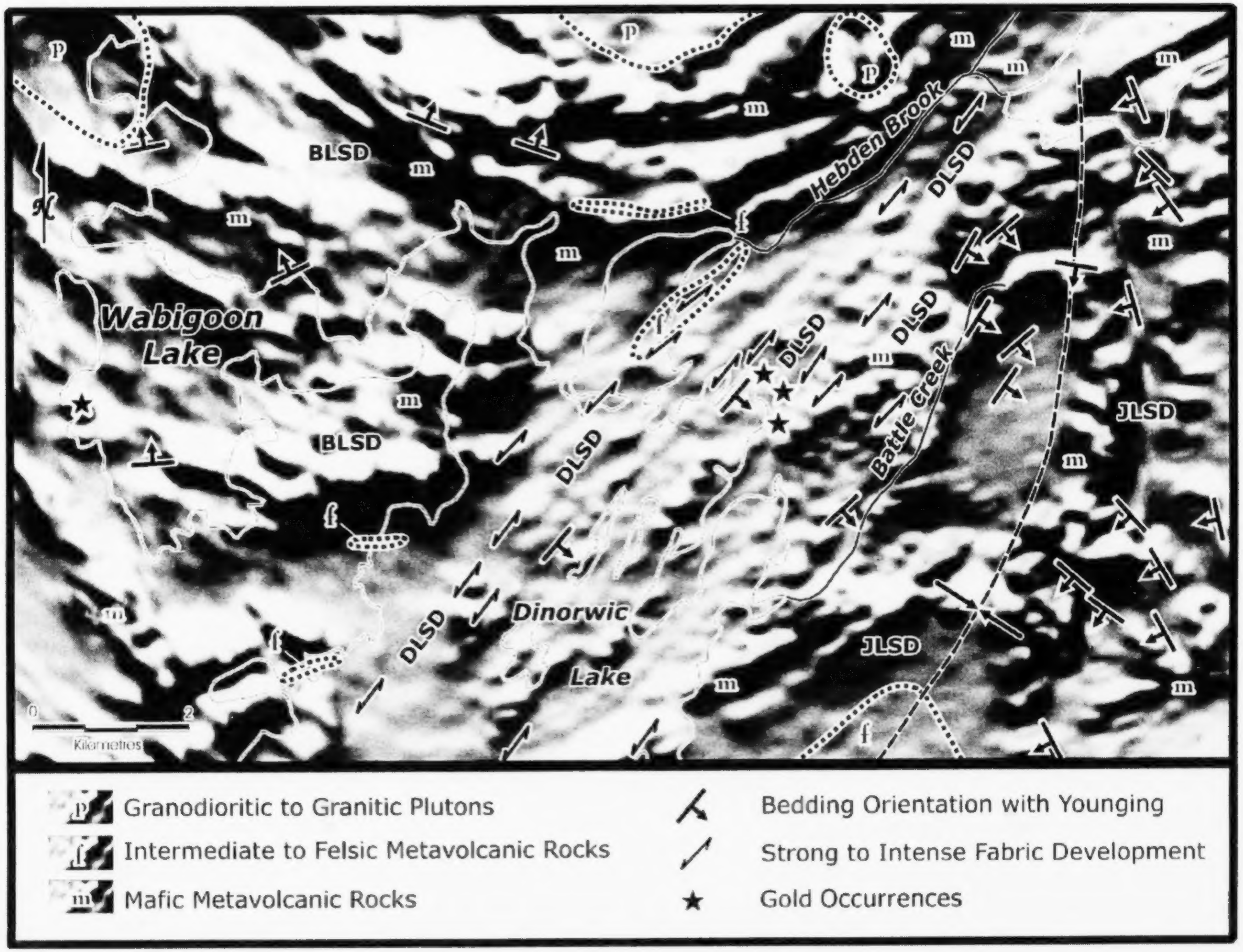
p
p
p
m
BLSD
Hebden Brook
DLSD
f
Wabigoon
Lake
BLSD
DLSD
Battle Creek
JLSD
Dinorwic
Lake
JLSD
N
0
2
Kilometres
p Granodioritic to Granitic Plutons
f Intermediate to Felsic Metavolcanic Rocks
m Mafic Metavolcanic Rocks
Bedding Orientation with Younging
Strong to Intense Fabric Development
★ Gold Occurrences

Figure 10.1. Generalized geology of the Dinorwic area superimposed on a shadowed image of the total magnetic field.

upper greenschist facies predominate with narrow amphibolitic contact metamorphic aureoles adjacent to some of the plutons. The main mineral exploration targets within the Wabigoon metavolcanics are volcanic-hosted base metal deposits that occur primarily in the upper portion of the sequence and gold mineralization associated with carbonate ± quartz alteration and veining.

LITHOLOGY

The Dinorwic area occurs within the Atikwa domain and, with the exception of several small, late intrusions, is underlain by the Wabigoon metavolcanics (Figure 10.1).

Mafic metavolcanic rocks dominate the Wabigoon metavolcanics in the Dinorwic area. Massive and pillowed flows are approximately subequally abundant with minor, widely distributed flow breccia and hyaloclastite. Massive flows range from fine to medium grained. Many of the pillowed flows and some of the massive flows are moderately vesicular. Equigranular flows are most abundant with conspicuous moderate to coarse plagioclase porphyritic flows occurring locally. Massive flows include both magnetite-poor (magnetic susceptibility ~0.5 to 1.0) and magnetite-rich (magnetic susceptibility commonly greater than 50) varieties, whereas the pillowed flows consistently have magnetic susceptibilities comparable to the magnetite-poor massive flows. The colour of both weathered and fresh surfaces is highly varied due to a range in intensity of a variety of types of alteration including carbonatization (both calcitic and ferroan carbonate), silicification and epidotization.

Intermediate to felsic metavolcanic rocks are a minor component of the Wabigoon volcanics. Very locally, they form mappable units up to several hundred metres in thickness, but are most commonly thin (<10 m) units interlayered with the predominant mafic metavolcanic rock. Many of these units are relatively massive and their origin is difficult to ascertain. Some units are characterized by the presence of bedding and/or lapilli-sized fragments indicating that they are pyroclastic or reworked fragmental deposits.

Sedimentary rocks are a very minor, widely distributed component of the Wabigoon metavolcanics. Most units contain an end-member, chemical metasedimentary component (chert) with a minor to significant clastic component. Local sulphide-rich zones associated with these horizons are interpreted to be, at least in part, syngenetic. These units are thin (<5 m; mostly <1 m) and have limited lateral extent.

STRUCTURE

The Dinorwic area is divisible into 3 structural domains that are referred to informally as the Butler Lake structural domain (BLSD), Dinorwic Lake structural domain (DLSD) and Jackfish Lake structural domain (JLSD)(*see* Figure 10.1). Within the BLSD (located to the west of Dinorwic Lake), the Wabigoon volcanics occur in a northward-facing homoclinal sequence. Many of these rocks are characterized by relatively low degrees of strain and have a weakly developed penetrative fabric approximately parallel to bedding. Much of the strain is partitioned into flow contacts, primary fragmental (flow breccia and hyaloclastite units) and interflow sedimentary units; these units are also generally characterized by the most intense, bedding-parallel fabric development. Locally, a second northeast- to north-northeast-trending fabric that may be related to the Dinorwic Lake structural domain (discussed below) transects the bedding and bedding-parallel fabric.

Within the JLSD, which is situated to the east of Dinorwic Lake, the Wabigoon volcanics are deformed about a disharmonic, closed, north-northeast-trending regional fold that plunges steeply to the southwest. Stratigraphic control of strain partitioning and bedding-parallel fabric development as described for the BLSD is also a conspicuous feature of this area. A weak, second northeast- to north-northeast-trending fabric is approximately parallel to both the axial surface of the regional fold and the fabrics developed within the DLSD.

The transition between these structurally distinct portions of the Atikwa domain corresponds to a well-foliated, intensely altered zone that is informally referred to as the Dinorwic Lake structural domain (DLSD) and is characterized by northeast- to north-northeast-trending fabrics. This domain approximately corresponds to the basin of Dinorwic Lake and extends to the north in an area approximately bounded by the northeast-trending segments of Hebden Brook and Battle Creek. The DLSD may be a northward extension of the Manitou Straits fault (Blackburn 1981; Blackburn et al. 1991). The area also corresponds generally to a zone characterized by a lower and less noisy aeromagnetic signature (*see* Figure 10.1). The intensity of fabric development within the DLSD ranges from weak to intense, but, in general, is much more intensely developed than within the bounding domains. An unusual feature of this domain is that, although many of the rocks are extremely fissile, the overall state of strain is remarkably low based on the geometry of pillows and vesicles. This observation, together with a paucity of asymmetric shear sense indicators, suggests that this broad, fissile, intensely altered zone is neither a high strain zone nor a shear zone. It is possible that narrow shear or high strain zones within this broader zone are concealed beneath extensive water-covered or poorly exposed areas.

ALTERATION

Many of the rocks in the Dinorwic area are moderately to intensely altered. This alteration includes both local, stratigraphically controlled alteration as well as more pervasive, regional, structurally controlled alteration that are described separately below.

Local Stratigraphically Controlled Alteration

Throughout much of the Dinorwic area outside of the DLSD, metavolcanic rocks are well preserved and characterized by very weak fabric development and background weak alteration with local zones of more intense alteration and fabric development. The background alteration consists of calcitic carbonate and less abundant epidote that has filled primary porosity (vesicles and interpillow spaces) and also occurs as fine-grained disseminated grains. Locally, interpillow carbonate encloses delicate, platy, exfoliated pillow selvage material. These observations suggest that this background alteration is related to synvolcanic to early diagenetic seawater alteration.

The more intense alteration observed locally is characterized by the presence of reddish weathering carbonate that is interpreted to reflect its more iron-rich (ferroan dolomite or ankerite) composition. This iron-bearing carbonate occurs as disseminations and in veins along with different proportions of quartz and calcitic carbonate. This type of alteration is associated with specific rock types and stratigraphic contacts including 1) flow contacts, especially where these are associated with brecciated flow tops; 2) chert ± sulphide units; and 3) thin interflow intermediate to felsic tuffaceous units. These units also characteristically have more conspicuous fabric development and have accommodated much of the strain. These structural attributes have undoubtedly played a role in generating the porosity and/or permeability that is responsible for this type of alteration being localized in these zones, but the development of these structures is itself strongly influenced by stratigraphy and the associated synvolcanic to early diagenetic development of hydrous mineral assemblages.

The more intense alteration is interpreted to be relatively late based on the moderately to undeformed character of veins. Locally, iron carbonate is observed to fill primary porosity and enclose delicate primary fragments as described above. This observation suggests that the iron-bearing carbonate overprints and locally replaces the early calcitic carbonate alteration.

Regional Structurally Controlled Alteration

Throughout large portions of the Dinorwic area, moderate to intense alteration is developed within and marginal to highly fissile zones that trend northeast to north-northeast. On a regional scale, this style of alteration is centred on the DLSD, much of which is moderately to intensely altered, however, this style of alteration also occurs along narrow, more widely spaced, north-northeast-trending to northeast-trending structures within the BLSD and JLSD.

The most extensive type of alteration consists of disseminated reddish brown weathering iron carbonate. Moderately deformed to undeformed veins consisting of iron carbonate and quartz in a range of proportions commonly occur along with the disseminated style of mineralization. Small areas within the regional iron-carbonate alteration are characterized by massive and pillowed mafic metavolcanic rocks with a very light gray colour and splintery fracture and are provisionally interpreted as zones of silicification. Quartz veining that is possibly related to this silicification contains angular fragments of iron carbonatized wall rock suggesting that the silicification may postdate the regional iron-carbonate alteration.

On regional as well as more local scales, this type of alteration is spatially associated with northeast- to north-northeast-trending zones characterized by being highly fissile although not necessarily highly strained. Characteristically, the alteration extends beyond the highly fissile zone into rocks that possess a very weak mineral foliation. The width of these zones is highly varied, but may be up to several hundred metres wide. Veining may be present throughout the zone of pervasive disseminated iron-bearing carbonate, but, in some cases, is observed to be most abundant in the fissile core and/or the outer edges of these alteration zones. The large area of iron-carbonate alteration associated with the DLSD may represent numerous closely spaced zones of this type.

MINERALIZATION

The Dinorwic area has potential for syngenetic, volcanic-hosted, base metal mineralization and late disseminated and vein-hosted gold mineralization. The most favourable area for base metal mineralization may be in the southwestern portion of the map area (*see* Figure 10.1) where numerous occurrences of massive and semi-massive sulphide mineralization were noted on the eastern part of Wabigoon Lake and western shore of Dinorwic Lake. These sulphide occurrences are either associated with cherty interflow metasedimentary horizons or occur within pillowed mafic metavolcanic rocks. All occurrences observed are dominantly pyritic, but locally contain minor amounts of chalcopyrite and possibly sphalerite.

Known occurrences of gold mineralization in the area are associated with quartz-carbonate veining containing one or more of tourmaline, pyrite, arsenopyrite, chalcopyrite and tetrahedrite (Parker 1989). Veins of this type are widespread within both the regional, north-northeast-trending alteration zones and the more localized stratigraphically controlled alteration zones described above and there is good potential for the discovery of additional gold mineralization.

Regional-scale iron-carbonate alteration in the Southworth Township area is considered to be favourable for gold mineralization. The general pattern of regional-scale iron-carbonate alteration with background (distal) calcitic carbonate containing more localized zones of silicification and veining observed in the Dinorwic area is comparable in many respects with that described for the area of the Red Lake gold camp (Parker 2000). The main differences between the 2 areas include the presence of abundant ultramafic metavolcanic rocks in the Red Lake area and the interpretation that the backgound calcitic carbonate alteration in the Dinorwic area significantly predates iron-carbonate alteration. These differences notwithstanding, the large area of iron-carbonate alteration within Southworth Township is proposed as a prime target for gold exploration.

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11. Project Unit 00-012. Preliminary Assessment of Isotopic Characteristics of Plutons within the Western Wabigoon Subprovince

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INTRODUCTION

The purpose of this contribution is to present a preliminary summary of isotopic data acquired as a component of an ongoing project to address the tectonic and metallogenic significance of mineralized and unmineralized plutonic rocks in the western Wabigoon Subprovince. The isotope work presented in this report was supported by the Operation Treasure Hunt Initiative.

The western Wabigoon Subprovince is interpreted to be a juvenile, late Neoarchean (~2713–2775 Ma) volcanic arc that was tectonically juxtaposed against (possibly overthrusting) an older (2.85–3.17 Ga) Winnipeg River Subprovince at approximately the same time (2707±7 Ma) as cessation of widespread juvenile Wabigoon Subprovince magmatic activity (Beakhouse and McNutt 1991). Subsequent magmatic activity is dominantly related to intracrustal melting of tectonically thickened crust in the Winnipeg River Subprovince and along the northern edge of the Wabigoon Subprovince, but minor, small, widely distributed plutons with a possible mantle component are also present. Many of these small, late plutons exhibit a close spatial relationship with gold ± copper ± molybdenum mineralization (Blackburn 1981).

This ongoing project is designed to address a number of problems as follows:

- the petrogenesis of late plutons
- the extent to which late plutons may have interacted with older crust
- the geographic and temporal constraints on possible interaction of late, mantle-derived magmas with older crust
- the characteristics of mineralized and unmineralized plutonic systems and possible application to predictive metallogeny.

RESULTS

All isotopic analyses were completed at the University of Alberta Radiogenic Isotope Facility. Analytical methods for Sm/Nd are discussed by Unterschutz et al. (2002). The data are tabulated (Table 11.1) and graphically represented as a function of their age in Figure 11.1. Ages are mostly based on high-precision U/Pb ages (Corfu 1988; Davis and Edwards 1986; Davis and Smith 1991; Davis, Blackburn and Krogh 1982; Beakhouse, McNutt and Krogh 1988), but several of the ages for the ~2700 Ma plutons are estimated from field relationships.

Most of the samples are from small, postvolcanic and late- to posttectonic plutons intruding the western Wabigoon Subprovince. To serve as a point of reference, several samples were also collected from large synvolcanic batholiths within the western Wabigoon Subprovince, as well as several late, crustally derived plutons from the Winnipeg River Subprovince.

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Table 11.1. Preliminary neodymium isotopic data.

Sample	Unit	Rock Type	Age	Easting	Northing	ε_{Nd}
Wabigoon – Synvolcanic						
84GPB242	Atikwa Batholith	Granodiorite	2732 Ma	561630	5493000	+3.5
84GPB258	Atikwa Batholith	Granodiorite	2732 Ma	569150	5497465	+3.3
00GPB7012	Aulneau Batholith	Granodiorite	2715 Ma	417567	5468568	+2.3
Winnipeg River – Late Plutons						
99GPB2	Lount Lake Batholith	Granodiorite	2702 Ma	400240	5507530	–2.0
99GPB5	Marginal granodiorite	Granodiorite	2709 Ma	388920	5513690	–2.1
99GPB6	Trout Lake pluton	Quartz diorite	2700 Ma	372620	5508860	–0.5
Wabigoon Postvolcanic Plutons						
84GPB116	Godson Lake quartz diorite	Quartz Diorite	~2700 Ma	518115	5491500	+1.7
00GPB7003	Hartman pluton	Granodiorite	~2700 Ma	538195	5508797	+0.7
00GPB7005	Sandybeach Lake pluton	Quartz diorite	~2700 Ma	541920	5514930	+1.8
00GPB7008	Red Cliff Bay pluton	Granodiorite	~2700 Ma	403636	5486358	+1.2
00GPB7014	Kishquabik Lake pluton	Quartz monzodiorite	~2700 Ma	438986	5478853	+1.3
00GPB7018	Stephen Lake pluton	Quartz diorite	2699 Ma	442857	5457249	+1.6
00GPB7033	Stephen Lake pluton	Quartz monzodiorite	2699 Ma	439565	5461121	+1.4
00GPB7035A	Scattergood Lake pluton	Granodiorite	~2700 Ma	522635	5457967	+1.1
00GPB7037A	Taylor Lake pluton	Quartz monzodiorite	2695 Ma	525267	5466840	+1.1
00GPB7042	Sultana Island pluton	Quartz monzodiorite	2700 Ma	398744	5506797	+0.3
00GPB7044	Sultana Island pluton	Diorite	2700 Ma	397545	5505893	+0.1
00GPB7047	Canoe Lake pluton	Quartz diorite	2709 Ma	362548	5499617	+1.9
00GPB7049	Canoe Lake pluton	Tonalite	2709 Ma	361864	5499242	+2.0
00GPB7052	Winnetka Lake stock	Granodiorite	~2700 Ma	364370	5509015	–0.4
00GPB7054	Granite Lake pluton	Granodiorite	~2700 Ma	369045	5508408	–0.2
00GPB7056	Island Lake pluton	Quartz diorite	~2700 Ma	403961	5514503	+0.3
00GPB7059	Jones Road stock	Granodiorite	~2700 Ma	398955	5511529	+0.0

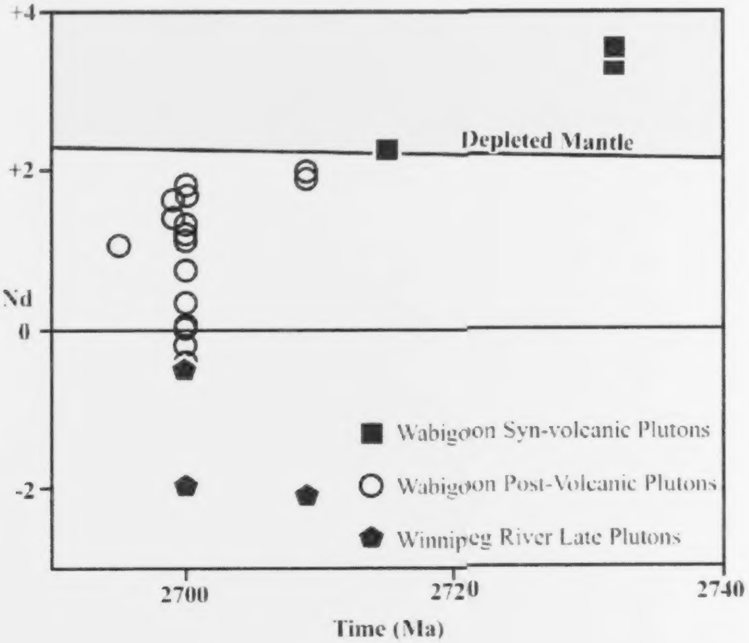

Figure 11.1. Neodymium evolution diagram. Depleted mantle estimate is *from* DePaolo (1980).

DISCUSSION

The isotopic characteristics of the synvolcanic plutons are similar to estimates for Neoarchean depleted mantle and are consistent with the hypothesis that the western Wabigoon Subprovince originated as a juvenile magmatic arc with no evidence for involvement of older continental crust. Two samples of biotite granodiorite from the Winnipeg River Subprovince have $\varepsilon_{Nd} \sim -2$ which is consistent with these rocks being derived by partial melting of metatonalite (~3.0 Ga), which occur in this subprovince (Beakhouse and McNutt 1991). A quartz diorite of possible sanukitoid affinity from the Winnipeg River Subprovince has ε_{Nd} (–0.5) intermediate between those of crustal melts and depleted mantle.

Postvolcanic, late- to posttectonic plutons in the western Wabigoon Subprovince are characterized by ε_{Nd} ranging from –0.4 to +2.0. Three isotopically and geochemically distinct reservoirs may contribute to the petrogenesis of these plutons:

- depleted mantle
- older (average ~3.0 Ga) intermediate to felsic crust (Winnipeg River Subprovince)
- metasomatically enriched, long-term depleted mantle

The isotopic data alone are difficult to reconcile with uncontaminated derivation from either depleted mantle or older intermediate to felsic crust. Some of these plutons have possible affinity with the sanukitoid suite for which an enriched, long-term deleted mantle source has been proposed (Shirey and Hanson 1984). The isotopic characteristics of such a source could be similar to those of these late plutons, but is a function of a number of variables including the timing of metasomatism and the nature of the enrichment, neither of which is easily constrained. The isotopic data are permissive of either a metasomatized mantle source or some mixture of 2 or more of these possible reservoirs. Investigations of the petrology and geochemistry of these plutons, together with further isotopic work are underway to further constrain the petrogenesis and tectonic and metallogenic significance of these plutons.

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12. Project Unit 02-005. Reconnaisance Survey of the Proterozoic Mafic and Ultramafic Intrusions of the Southern Portion of the Nipigon Embayment

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INTRODUCTION

This project involved the reconnaissance geochemical sampling of mafic and ultramafic intrusions in the southern portion of the Nipigon embayment, extending north from Highway 11 to just south of Lake Nipigon (Figure 12.1) and also included limited sampling of the English Bay intrusion. The ultramafic rocks of 3 mafic to ultramafic intrusions are currently being explored for their potential to host platinum group element (PGE) mineralization. Additional exploration in the area is attempting to locate more of these ultramafic intrusions. The objective of this project is to provide a better understanding of the igneous petrogenesis of the intrusive rocks, the relationship between the diabase sills and the ultramafic intrusions, and the intrusive relationships with the Quetico Subprovince and Sibley Group country rocks. The intention is to provide insight on the factors controlling the location of the ultramafic rocks, and the origin and mode of formation of the PGE mineralization. This insight will be useful for future mapping projects, as well as prospecting and mineral exploration activity, in the Nipigon area.

The southern portion of the Nipigon embayment is located approximately 80 km northeast of Thunder Bay, between Lake Superior and Lake Nipigon. Access is provided by Highway 11, the Black Sturgeon Road, the Dorion Cut-off Road, Highway 585, and the logging roads extending from these roads. Previous geological mapping by Coates (1972) covered the area at a scale of 1:63 360, with mapping by Sutcliffe (1982a, 1982b) covering the area immediately south of Lake Nipigon at scale of 1:50 000. Mineral exploration and prospecting was initially conducted mainly for iron ore in the 1900s with little subsequent activity until the discovery of copper mineralization near Disraeli Lake in 1965 (Coates 1972). Since 1965, exploration activity for copper has been sporadic. Circa 1978, there was a brief period of exploration for uranium (Fenwick et al. 1980). Exploration for PGE mineralization intensified circa 1998, starting with the work on the Seagull–Leckie Lake intrusion (Osmani and Rees 1998).

GENERAL GEOLOGY

The area is underlain by Archean metasedimentary, metavolcanic, and felsic intrusive rocks of the southern Wabigoon and Quetico subprovinces, which are unconformably overlain by Proterozoic metasedimentary rocks of the Sibley Group (1340±33 Ma: Wanless and Loveridge 1978) (*see* Figure 12.1). Proterozoic mafic to ultramafic intrusive rocks and diabase sills intrude rocks of the Wabigoon and Quetico subprovinces and the Sibley Group. Metasedimentary rocks of the Wabigoon and Quetico subprovinces consist of northeast-striking, steeply dipping, well-bedded wacke and siltstone. Regionally continuous iron formations are traceable by airborne geophysical magnetic surveys and appear to correlate with the iron formations within the metasedimentary subbelts of the Beardmore–Geraldton Belt of the southern Wabigoon Subprovince (Gupta 1991). Metavolcanic rocks form a thin band reported

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Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.12-1 to 12-10.

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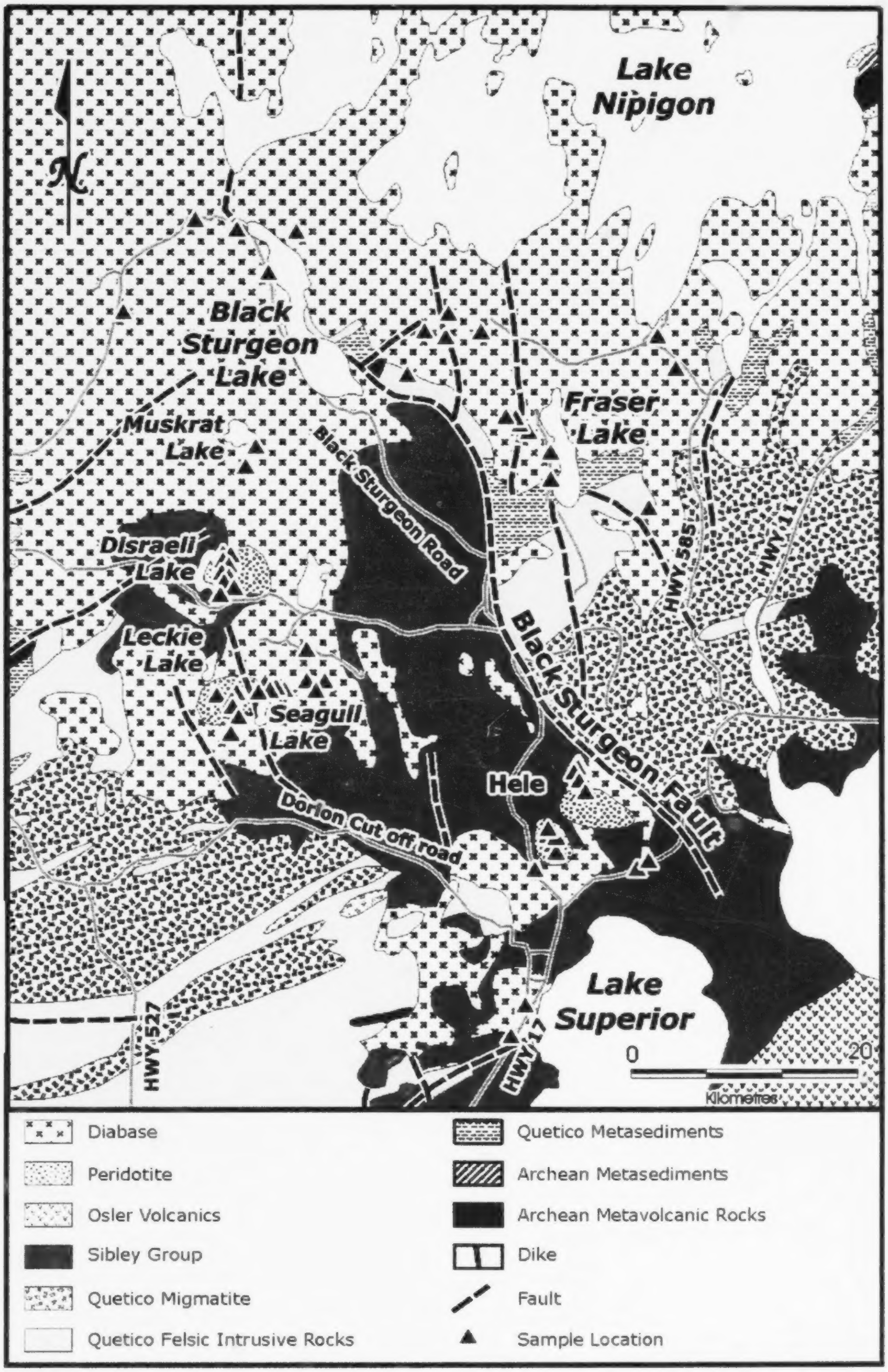
N
Lake Nipigon
Black Sturgeon Lake
Muskrat Lake
Fraser Lake
Black Sturgeon Road
Disraeli Lake
Leckie Lake
Seagull Lake
HWY 585
HWY 11
Black Sturgeon Fault
Hele
Dorion Cut off road
Lake Superior
HWY 527
HWY 17
0
20
Kilometres
Diabase
Peridotite
Osler Volcanics
Sibley Group
Quetico Migmatite
Quetico Felsic Intrusive Rocks
Quetico Metasediments
Archean Metasediments
Archean Metavolcanic Rocks
Dike
Fault
Sample Location

Figure 12.1. Geology of the southern portion of the Nipigon Embayment.

to crop out east of Black Sturgeon Lake (Coates 1972), and may represent the northeast extension of the Max Lake greenstone belt located to the west. Metamorphism increases from the Wabigoon Subprovince into the Quetico Subprovince, with the Quetico Subprovince metasedimentary rocks metamorphosed to upper greenschist to amphibolite grade, and commonly containing biotite with varied amounts of garnet and/or andalusite. Intermediate to felsic intrusive rocks intrude the Quetico Subprovince metasedimentary rocks, with a hematized quartz monzonite observed east of Frazer Lake and a pegmatitic monzogranite east of Black Sturgeon Lake. Metamorphism and deformation increases to the south in the Quetico Subprovince, with the development of migmatite in the southern portion of the area. The Sibley Group metasedimentary rocks consist of relatively flat-lying red arenaceous dolomite, chert-carbonate stromatolitic marble, and red argillaceous dolomite of the Rossport Formation overlain by purple shale of the Kama Hill Formation. There are 3 pyroxene peridotite to olivine gabbro intrusions forming bodies a few kilometres in diameter that have intruded metasedimentary rocks of the Quetico Subprovince and Sibley Group. A series of Proterozoic olivine diabase sills, up to 200 m thick, intrude all other units in the area and are chilled against the ultramafic intrusions. Diabase sills, located on the western side of Lake Nipigon, have ages of 1108.8 +4/–2 Ma, which are bracketed by an quartz-feldspar porphyritic rhyolite (1107 +4/–2 Ma) near the base and a rhyolite flow (1097±3.7 Ma) near the top of the Osler Group (Davis and Sutcliffe 1985). A number of northeast-trending faults are subparallel to the Wabigoon–Quetico subprovince boundary and the regional fabric of the Quetico Subprovince. The Black Sturgeon fault is one of a series of subparallel northwest-trending faults interpreted to predate the emplacement of the diabase sills, and which may represent the failed arm of the Keweenawan Midcontinent Rift.

Mafic to Ultramafic Intrusive Rocks

Three mafic to ultramafic intrusions, Disraeli, Seagull–Leckie, and Driftstone–Hele, are present in the area south of Lake Nipigon. A small area of ultramafic intrusion has been recently exposed in the area southwest of the Hele intrusion, and could be either a separate intrusion or extension of the Hele intrusion (*see* Figure 12.1). These intrusions are composed of pyroxene peridotite and olivine gabbro with minor monzogabbro, and are hosted by Sibley Group and Quetico Subprovince metasedimentary rocks. The diabase sills have chilled contacts with these intrusions.

The peridotite is medium to coarse grained, massive, dark green to greenish black and composed of predominantly olivine and pyroxene with less than 10% plagioclase and 1 to 2% reddish brown mica. Outcrops of the peridotite generally have a very low relief and are deeply weathered resulting in a pebbly black sand regolith. These rocks were classified as a peridotite in the field, but petrographic examinations indicate that these rocks are pyroxene peridotite composed of a mixture of wehrlite and lherzolite (Seagull: Osmani and Rees 1998; Disraeli: Bowdidge 1999) with lesser amounts of melagabbro (Hele: Cunnison and Pyke 2001). These examinations also indicate that the peridotite commonly has orthocumulate to mesocumulate textures. Contacts between the peridotite and olivine gabbro, and between the peridotite and diabase sills were not observed.

The olivine gabbro is medium grained, massive, dark green composed of pyroxene, olivine and plagioclase. The olivine gabbro resembles the gabbro forming the diabase sills and the 2 units are difficult to distinguish in highly weathered outcrops and in areas where the olivine gabbro is in contact with the country rocks. A higher olivine content, generally greater than 10%, and a lower magnetic susceptibility, 5 to 10 × 10^{-3} for the gabbro versus 25 to 50 × 10^{-3} for the diabase, generally distinguishes the olivine gabbro from the diabasic gabbro. An olivine gabbro is present in all 3 intrusions, and appears to form the border phase to the peridotite core zone in the Hele and Seagull intrusions. The relationship between the olivine gabbro and peridotite is not known as the contacts are rarely observed. A 50 m thick olivine gabbro sill occurs in the upper portion of the peridotite in the Seagull intrusion (Osmani and Rees 1998) and inclusions of pyroxene-rich mafic to melagabbro are reported from the upper portion of the

Hele intrusion (Cunnison and Pyke 2001). Work in the Kitto intrusion, an intrusion geochemically and petrographically similar to these intrusions, indicates that the peridotite and olivine gabbro probably formed by fractional crystallization from a single pulse of magma (Hart, terMeer and Jolette 2002).

A monzogabbro was observed along the contact between the Fox Mountain dike and the Disraeli intrusion, and an area of monzogabbro to monzonite was outline along the northwest edge of the Disraeli intrusion by Bowdidge (1999). Interstitial graphic, quartz-alkali feldspar textures in the monzogabbro were interpreted by Bowdidge (1999) to be the result of the assimilation of Sibley Group metasedimentary rocks. An olivine gabbro with pink feldspar, resembling a monzogabbro, is common along the contact with the Sibley Group metasedimentary rocks in the Hele and Seagull intrusions. The presence of pink feldspar, and the decrease in this feldspar away from the country rock contact, was initially interpreted to be the result of the assimilation of hematite from the Sibley Group metasedimentary rocks. The contact between the olivine gabbro of the Seagull intrusion and a diabase sill was observed north of Seagull Lake, where the diabase has an irregular, polygonal-textured chilled contact against the gabbro.

Diabase Sills

A series of undulating, generally flat-lying to shallow-dipping Proterozoic diabase sills intrude all other rock units in the area. The diabase sills are commonly composed of massive, medium- to fine-grained feldspar and pyroxene with trace to 3% fine-grained olivine and 1 to 2% magnetite. Coarse-grained diabase was only observed in some of the sills intersected in the drill holes from Muskrat Lake by McVicar Resources Ltd., and in the English Bay area by Corona Gold Corporation. Irregular patches of very coarse-grained amphibole and feldspar are also common near the upper contact of the thicker sills. This coarse-grained diabase may contain irregular, 0.25 to 0.5 cm miarolitic cavities, possibly containing black biotite.

The most common observed style of contact for the diabase sills is a polygonal jointed, aphanitic to very fine-grained diabase with a variable content of fine-grained feldspar phenocrysts. Some contacts contain less than 1%, subangular, pebble to boulder sized xenoliths of country rock surrounded by dark grey reaction rims and occasionally cut by the polygonal joints (Photo 12.1). The diabase increases in grain size to fine to medium grained over less than 1 m, with generally no evidence of assimilation of country rock. A hybrid style of contact was observed in one location in a rock quarry immediately north of Highway 17. Rounded, pebble-sized xenoliths of Sibley Group metasedimentary rock are recrystallized to quartz, feldspar and biotite, forming 30% of a rock with a fine-grained biotitic diabase matrix. About 150 m to the south along the highway, xenoliths of Sibley Group metasedimentary rocks, tens of metres in size, are surrounded by diabase. The metasedimentary rocks have moderately well-developed calc-silicate metamorphosed rinds where the surrounding diabase lacks a chill contact.

The sills occur as major and minor sills, with the major sills ranging up to 200 m in thickness and the minor sills being generally less than 5 m thick. Examples of the minor sills occur in widely scattered locations, such as along Highway 11 east of Nipigon, on a logging road north of Seagull Lake, and in the diamond-drill core of 3 holes in the Muskrat Lake area. The relationship between the major and minor sills is not known and there are a number of possible interpretations, including the minor sills being the leading edge of a major sill, branches from major sills following less favourable structures, or separate lower volume magma pulses. Most of the minor sills appear to be very fine-grained diabase, although the diabase in the Muskrat Lake diamond-drill holes is very coarse grained. However, some of the minor sills may be related to the peridotite intrusions, such as a 0.5 m thick sill sampled along Highway 17, which contains abundant pink feldspar similar to the olivine gabbro of the Hele intrusion.

Fox Mountain dike is a medium-grained, massive, olivine gabbro dike that has chilled contacts with a monzogabbro unit of the Disraeli intrusion. The olivine gabbro generally resembles the diabase of the Nipigon sills in the few outcrops examined during this project. A portion of the dike was reported to host plagioclase glomeroporphyritic textures with phenocrysts up to 3 cm across (Bowdidge 1999). The dike is oriented subparallel to the Black Sturgeon fault and may have intruded along a subparallel structure.

The Nipigon diabase sills are considered to be related to the same magmatic event—opening of the Midcontinent Rift—as the Logan sills located to the south in the area of Thunder Bay (Sutcliffe 1991). However, the Nipigon diabase contains olivine as a minor mineral phase in contrast to the quartz tholeiites of the Logan sills (J. Franklin and R. Middleton, East West Resource Corporation, personal communication, 2001). The presence of olivine versus quartz probably has implications with respect to the formation of the Nipigon and Logan sills including different magma sources, depth of melting, and/or degrees of modification before intrusion.

English Bay Intrusion

The English Bay intrusion (1536+10/–2.3 Ma: Davis and Sutcliffe 1985) is located along the northwest shore of Lake Nipigon, approximately 170 km north of Thunder Bay. Diamond drilling by Corona Gold Corporation in 1998, for Olympic Dam-style of mineralization, intersected massive, moderately to strongly, hematized and sercitized, brick red quartz-feldspar porphyry, feldspar porphyry, and granite (Wood and Drost 1998). An examination of the diamond-drill core suggests that these rocks range from alkali feldspar granite to alkali feldspar syenite to granite. An intrusive breccia near the contact of the intrusion contains abundant xenoliths up to 40 cm in diameter, commonly with gneissic textures. The intrusion breccia exposed along the logging road north of the drill core pile contains a variety of xenoliths including the most abundant light grey to mauve, quartz porphyritic gneiss in massive

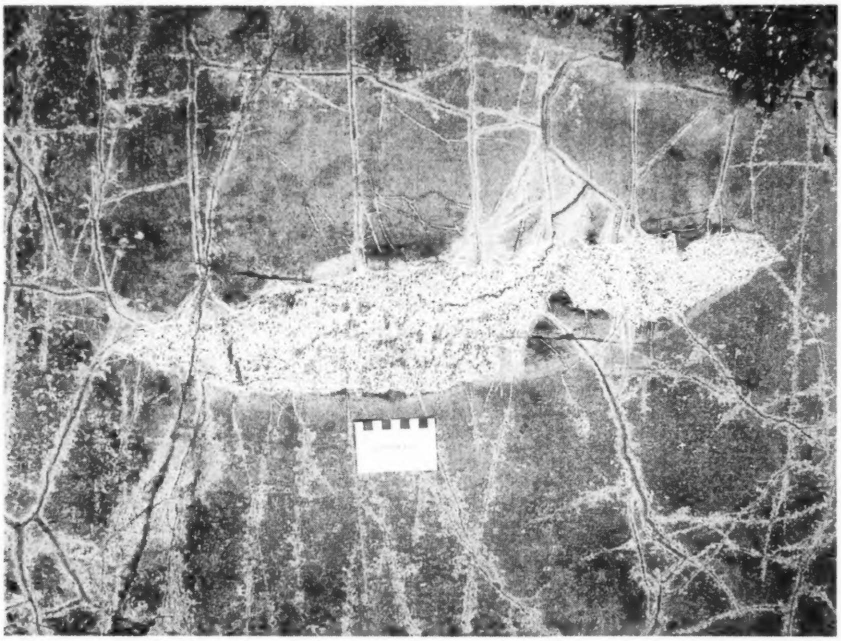

Photo 12.1. Photograph of a xenolith of Quetico Subprovince migmatite and fine-grained white feldspar phenocrysts in chilled upper diabase contact.

quartz-feldspar porphyritic granite to syenite. The intrusion is intruded by medium- to coarse-grained diabase sills with chilled contacts. The English Bay intrusion is located close to the northern projection is the Black Sturgeon Lake fault, and is currently being explored by East West Resource Corporation (East West Resource Corporation 2002). A number of representative samples of the intrusion and diabase sills were collected for whole rock analyses and petrographic examination.

STRUCTURAL GEOLOGY

Three major fault trends were outlined by Coates (1972):

1. a series of northwest-trending faults with predominant dextral displacement
2. a series of northeast-trending faults subparallel to the regional fabric of the Quetico Subprovince
3. a number of north-trending faults with variable dextral and sinistral displacements

The northwest-trending faults, which include the Black Sturgeon fault, are probably an expression of the failed arm of the Midcontinent Rift (e.g., Franklin et al. 1980). In addition to controlling the emplacement of the diabase sills, these northwest-trending faults may have partially controlled the emplacement of the peridotite intrusions. The Black Sturgeon fault has been interpreted to be a series of *en échelon* northwest-trending faults, which formed an asymmetric basin or graben approximately 20 km wide (Coates 1972). Vertical displacements of 213 to 305 m were estimated from lithologic offsets on the Black Sturgeon fault by Coates (1972), but a 420 m depth to the Sibley Group metasedimentary rocks, estimated by Sutcliffe (1986), may represent an upper limit on the vertical displacement. Sutcliffe (1986) interpreted offsets of approximately 4 km in airborne geophysical magnetic anomalies to indicate a sinistral horizontal displacement.

The few observed sill contacts generally dip less than 30° to the south, although the contacts often undulate by tens to hundreds of metres vertically, which hinders the accurate determination of dip direction. Large-scale columnar jointing is commonly observed in the cliff exposures of the major sills, but is not always evident in outcrop. Arcuate jointing, similar to that described in the Beardmore area by Hart, terMeer and Jolette (2002), was observed in a few locations. The sills are cut by later structures that are probably re-activated, pre-existing faults, with a good example exposed in the cliff face visible along the southeast side of the Black Sturgeon Road in Hele Township.

Alteration and Mineralization

The peridotite is commonly deeply weathered and may be capped by a black sand regolith tens of centimetres thick, probably produced by extreme alteration of the olivine and disintegration of the rock. As a result of this deep weathering, the peridotite outcrops are generally small with a very low relief. Serpentine alteration is varied and restricted to some fractures and probably is a result of alteration of olivine during the cooling of the intrusion and subsequent reaction with circulating groundwater.

The olivine gabbro is generally also deeply weathered, forming small low-relief outcrops. Alteration is usually restricted for minor development of chlorite along fractures. The presence and abundance of pink feldspar correlates with proximity to the contact with the Sibley Group metasedimentary rocks. The initial interpretation was that the pink feldspar was the result of hematization resulting from the assimilation of the metasedimentary rocks. However, an examination of the geochemistry from the Hele and Seagull intrusions (Cunnison and Pyke 2001; Osmani and Rees 1999) suggests that the presence of pink feldspar may correlate with a higher K_2O content rather than a higher Fe_2O_3 content.

Weathering in the diabase is varied, ranging from 1 to 2 cm to 10 cm in depth, with alteration of the olivine and magnetite being most pronounced. Alteration is generally restricted to joints and fractures near the contacts with the country rocks, with varied development of zeolite minerals, amphibole or amphibole-feldspar. The amphibole and feldspar are usually very coarse grained and may be bounded by very fine-grained chlorite. Cavities, initially classified as miarolitic, occur in the coarser.grained diabase commonly located in close proximity to the sill contacts. The presence of country rock xenoliths in many of the chilled diabase contacts suggests that material may have been incorporated from a number of different sources, and these cavities could also be the result of assimilation of fluid or volatile-rich Sibley Group metasedimentary rocks. However, the lack of evidence of extensive assimilation in the diabase suggests that the metasedimentary rocks were probably not the main source of a fluid or volatile phase. The cavities are probably miarolitic, and are the result of late-stage magmatic fluids and indicate that the sills were emplaced and crystallized at a shallow depth.

Mineralization was not observed during this project, but samples of the peridotite, including the Haskell showing in a peridotite southwest of the Hele intrusion, were submitted for analyses. The only known surface exposure of mineralization within a peridotite is located in partially in-filled trenches on the Seagull intrusion. Sampling of these trenches by Avalon Ventures Limited returned assays up to 2610 ppb Pt and 1145 ppb Pd in the Central Zone (Osmani and Rees 1998). A number of diamond-drill holes in the Seagull intrusion also intersected PGE mineralization at or near the basal contact with metasedimentary rocks of the Quetico Subprovince (East West Resource Corporation 2001). The best intersection returned 1.71 ppm Pt and 1.87 ppm Pd over 2.1 m in a biotite pyroxenite containing 10% disseminated to net-textured pyrite, pyrrhotite and minor chalcopyrite (Durham 2000).

A very coarse-grained tremolite-carbonate rich assemblage was developed in an areneous dolomite of the Sibley Group metasedimentary rocks in contact with a diabase sill located along Highway 17. Development of this mineral assemblage suggests a potential for the development of skarn style, possibly copper-gold-magnetite mineralization in the dolomite and marble altered by the diabase sills or peridotite. Mineralization could originate from either the intrusions, or from the metasedimentary rocks because bornite is a common accessory mineral in the marbles.

GEOCHEMISTRY

All samples have been submitted for a full analytical suite of major and trace elements plus gold, platinum and palladium, and the results are pending. A limited amount of whole rock geochemistry, with a limited set of trace elements, is currently available for the diabase sills, and the peridotite and olivine gabbro of the Hele and Seagull intrusions (Cunnison and Pyke 2001; Osmani and Rees 1998). Following the IUGS classification as proposed by LeMaitre et al. (1989), these medium- to coarse-grained, cumulate-textured intrusive rocks should be classified as wehrlite and lherzolite, which are collectively termed pyroxene peridotite. In the IUGS recommendations, picrite is a subdivision on the total alkali-silica (TAS) classification, and the TAS is intended for use with fine-grained volcanic rocks. Application of the TAS classification to cumulate igneous rocks may produce an erroneous classification (LeMaitre et al. 1989; LeBas 2000).

Initial examinations of the geochemistry suggests that the Seagull and Hele peridotite and olivine gabbro samples are similar to the olivine and augite porphyritic basalts of the Lower Suite of the Osler Group (Lightfoot, Sutcliffe and Doherty 1991). These rocks are also similar to the peridotite and olivine gabbro of the Kitto intrusion (Hart, terMeer and Jolette 2002). The diabase sills are similar geochemically to the basalt flows of the Upper Suite of the Osler Group located to the south, and may have formed from the same magma feeder system as the volcanic rocks (Sutcliffe 1987; Lightfoot, Sutcliffe and Doherty 1991).

RECOMMENDATIONS

A depletion in nickel and copper with increasing La/Sm ratios within some of the Osler Group volcanic rocks was interpreted by Naldrett and Lightfoot (1993) to be comparable to trends observed in the Noril'sk area. If either the peridotite or the diabase sills are part of the same magmatic system as the volcanic rocks, then the potential exists for magmatic nickel-copper sulphide mineralization related to these intrusions. The peridotite may have a higher potential for mineralization since evidence for the assimilation of crustal material, including possible sources of sulphur, is more common in these rocks. Detailed geochemical sampling is recommended to examine the potential for mineralization in both rock types.

The mapping and geochemical sampling by Sutcliffe (1986) and by Hart, terMeer and Jolette (2002) indicate that the sills do not represent a single cooling unit, and were formed by multiple pulses of magma. A better understanding of the petrogenesis of the sills may be possible through the sampling of detailed stratigraphic sections either in outcrop or in diamond-drill holes.

The deep-weathering profile common to the peridotite means that obtaining a fresh sample for geochemical analyses is difficult and that there are a limited number of outcrops to be sampled. Detailed sampling and re-logging of diamond-drill core would provide more detail than would be possible from outcrops alone. Re-analysis of pulps or rejects from the original sampling of the core may be useful in some cases if the material is still available.

Contact relationships indicate that the peridotite is older than the diabase sills, and there is the potential for a sill to overlie and mask the existence of a peridotite intrusion. Geophysical surveys may be a method of providing further information on the geology of the area. However, the more highly magnetic diabase sills would probably mask the less magnetic peridotite if a magnetic survey was conducted. Geochemical surveys would be an alternative means of obtaining information on the geology, especially lake sediment surveys as the lakes may provide "windows" through the diabase sills. A lake sediment survey completed by the Geological Survey of Canada (Friske, McCurdy and Cook 1990) indicates a good correlation between peridotite intrusions and coincident chromium-nickel anomalies. The data contained in a recent release of a more detailed survey by the Ontario Geological Survey (Dyer 2002) should be examined in detail for any unexplained anomalies.

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13. Project Unit 02-007. Paleomagnetic, Geochemical and U/Pb Geochronologic Studies of Mafic Dikes in Northern Ontario: Relevance to Mineralization Associated with the Nipigon Embayment and Kimberlites

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INTRODUCTION

Documentation of Proterozoic diabase dike swarms in Ontario has progressed slowly over the years. Osmani (1991) summarized the state of our understanding over 10 years ago. Proterozoic diabase dike swarms of at least 10 different ages intrude the Superior Province of northern Ontario (Osmani 1991; Fahrig 1987; Buchan and Halls 1990). Paleoproterozoic dikes, apart from those of the Molson swarm, are quartz tholeiite composed of plagioclase and pyroxene, typically with visible quartz and myrmekite. Neoproterozoic dikes are more alkalic and characteristically possess fresh olivine (*see* Table 17.1 of Osmani 1991). During the last 15 years, a major paleomagnetic and U/Pb geochronology program of Ontario dike swarms has been underway. The purpose is to distinguish the various dike swarms and examine their usefulness as structural elements to detect crustal uplift, tilting and rotation (Bates and Halls 1991; Halls and Zhang 1998; Buchan, Mortensen and Card 1993; Buchan, Halls and Mortensen 1996; Halls and Davis 2002). However, there remain significant gaps in our knowledge of the ages and origin of many of the dike swarms in Ontario. This current project is supported under an Ontario Geological Survey – University of Toronto Collaborative Project Agreement.

Proterozoic mafic magma systems have attracted exploration interest for their platinum group element (PGE) potential, especially the Keweenawan sills in the vicinity of Lake Nipigon. The Keweenawan Nipigon sills and associated ring dike systems have attracted strong exploration interest as possible host rocks for magmatic nickel-copper-PGE mineralization. However, the lateral dimensions of this magmatic province are poorly defined and are presently defined by the distribution of the Nipigon sills and associated ring dikes. However, it is possible that many of the dikes represent feeder systems beyond the current size of the Nipigon embayment.

It has been inferred (Naldrett and Lightfoot 1993) that the presence of the north-striking Black Sturgeon fault along the west side of Lake Nipigon in association with the Keweenawan intrusions bears some similarities to the structural and magmatic setting of the Noril'sk nickel-copper-PGE camp in Russia. However, the following questions remain: are the ring dike systems east and northeast of Lake Nipigon too far from the main magmatic centres to be of interest for mineral exploration?, or is the magma system extensive enough (judging from the eastward distribution of diabase dikes) to warrant a broader search for magmatic nickel-copper-PGE mineralization? There is no current evidence that Keweenawan diabase dikes occur east of Lake Nipigon, although their presence has been suggested (cf. Osmani 1991). One goal of this project is to sample dikes east of Lake Nipigon to test if the Keweenawan magmatic system extends beyond the sills on the eastern shore of Lake Nipigon.

Summary of Field Work and Other Activities 2002,
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The complex and variable mix of dike orientations east of Lake Nipigon and the uncertainty about assigning north- and northeast-striking dikes to specific swarms has demonstrated a need to distinguish these dikes from each other. Therefore, the objectives of this study are 1) to identify the different ages of dikes east of Lake Nipigon; 2) to correlate these dikes with known swarms outside the Lake Nipigon region wherever possible; and 3) to identify dikes that are associated with magmatic episodes known to be associated with magmatic nickel-copper-PGE mineralization. These objectives will be achieved by using a combined analysis of U/Pb geochronological data, paleomagnetism and major, minor and trace element lithogeochemistry.

A significant justification for studying the diabase dike systems in the eastern Wabigoon Subprovince arises from the recognition that 1) the north-striking dikes extend into the James Bay Lowlands (cf. Ontario Geological Survey 1992) where diamond-bearing kimberlite pipes have recently been discovered (Sage 1997); and 2) that northwest-striking dikes might have a direct relationship to deep fractures that controlled the emplacement of the kimberlite pipes. The active exploration for diamond-bearing kimberlite pipes in the Lowlands has stimulated an interest in understanding the structural controls for the emplacement of these pipes. Paleoproterozoic diabase dikes were injected along major fracture swarms arising from the emplacement of mantle plumes (e.g., Ernst and Buchan 2001). Explorationists have recognized a possible correlation between the presence of kimberlite pipes and major crustal faults. However, little public attention has been placed on the potential significance of the diabase dikes as aeromagnetic markers of deep fracture systems that could have controlled kimberlite pipe emplacement. For example, the early Jurassic kimberlite pipes in the vicinity of the Victor pipe near Attawapiskat River are distributed close to the Winisk fault (Figure 13.1). However, they also form a significant linear train along strike with a concentrated group of northwest-striking Matachewan dikes (*see* Figure 13.1) (also cf. Figure Area A, Zalnieriunas and Sage 1995; and the diabase dike traces in the James Bay Lowlands, Ontario Geological Survey 1992). Similarly, the Proterozoic kimberlite pipes farther west of the Victor pipe, known as the Kyle pipes (Sage 1997), occur close to a north-striking set of Marathon dikes (*see* Figure 13.1). These observations suggest that the different ages of kimberlite pipes (Mesoproterozoic versus early Jurassic) were intruded along plume-generated fractures accompanying the diabase dikes of different Paleoproterozoic ages (2121 Ma (Marathon) versus 2446 Ma (Matachewan)). Therefore, the diabase dikes may provide a prominent indication of regional fracture trends and their concentrations, which can be identified on airborne geophysical magnetic maps. It is noteworthy that an overlap of both Matachewan and Marathon dike sets occurs farther east of the Victor deposit near longitude 83° and the Winisk fault and might provide a test for this correlation between diabase dikes and kimberlite pipes. We need to explore why there is an apparent correlation between different groups of deep crustal fractures and younger kimberlite pipes. Are the Matachewan and Marathon fracture systems near the Winisk fault second-order (re-opened?) fracture "splays" associated with the fault? Did these fractures provide a preferred emplacement pathway for kimberlite pipe intrusions? A more concerted effort is clearly needed to understand the relation between these dike–fracture systems and the clusters and trains of kimberlite pipes, including those still hidden in and under the lowland cover rocks.

Another consideration in our study of these dike swarms was the recognition by Manson and Halls (1997) of broad crustal segments characterized by relative differences in thermal stability reflected in differences in radiometric age disturbance across the southern Superior Province. These segments are bounded by major northeast-striking faults. One broad northeast-striking segment, between the Kapuskasing Structural Zone and the Gravel River fault near Longlac, corresponds to a broad northeast-striking gap in known kimberlite pipes between Wawa and the Attawapiskat–Missisa intrusions in the northern James Bay Lowlands (cf. Zalnieriunas and Sage 1995). Whether these northeast-striking segments of relative contrast in crustal stability have a bearing on the spatial distribution of fracture systems that control the distribution of kimberlite pipes remains unclear.

In summary, there is economically relevant justification for re-examining the Proterozoic history of magmatism, fracture-generation and thermal perturbations across the Superior Province. Our contribution begins with the dike swarms in the region east of Lake Nipigon.

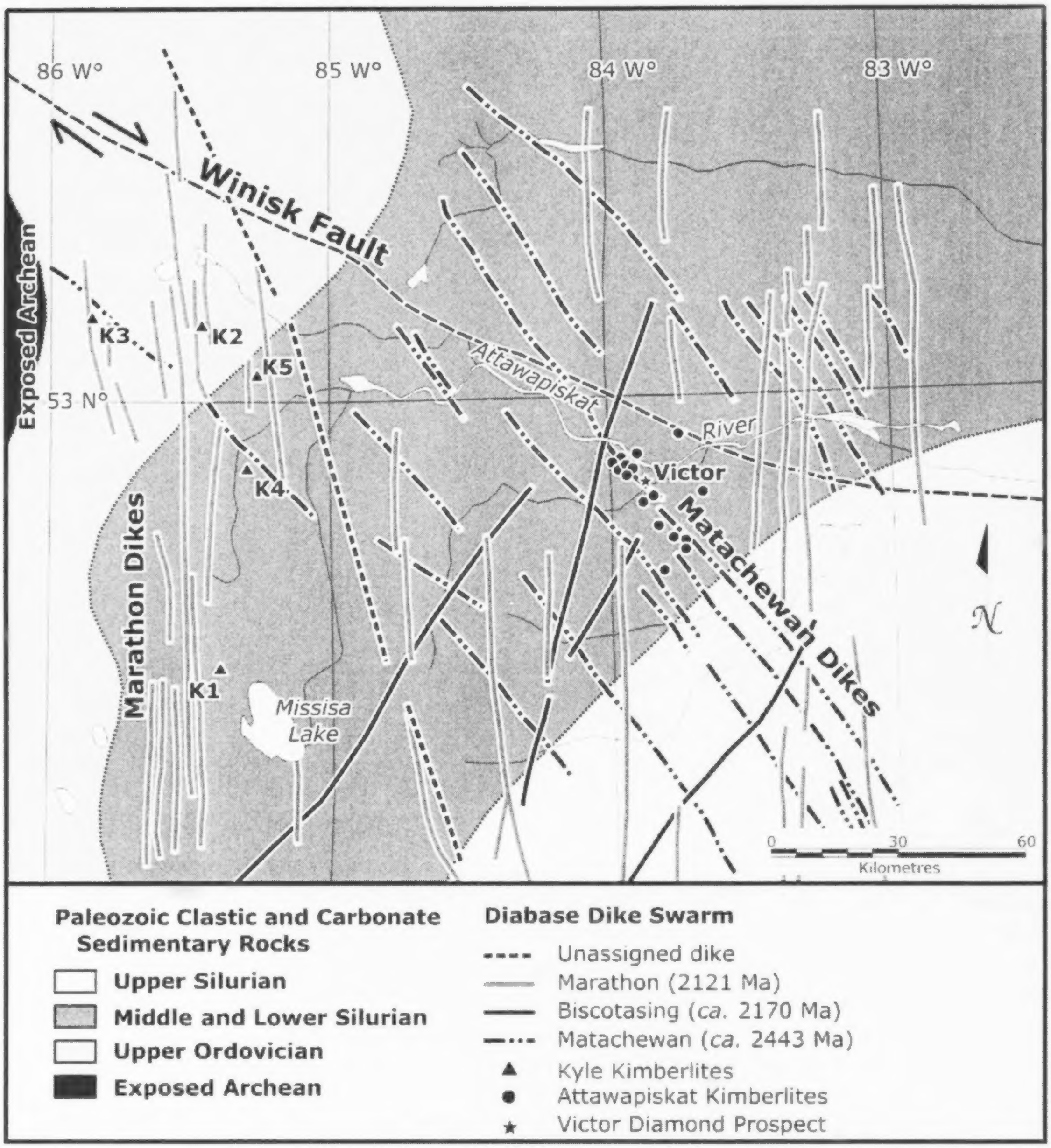
86 W°
85 W°
84 W°
83 W°
53 N°
Winisk Fault
Exposed Archean
K3
K2
K5
K4
K1
Marathon Dikes
Attawapiskat
River
Victor
Matachewan Dikes
Missisa Lake
N
0
30
60
Kilometres
Paleozoic Clastic and Carbonate Sedimentary Rocks
Upper Silurian
Middle and Lower Silurian
Upper Ordovician
Exposed Archean
Diabase Dike Swarm
Unassigned dike
Marathon (2121 Ma)
Biscotasing (ca. 2170 Ma)
Matachewan (ca. 2443 Ma)
Kyle Kimberlites
Attawapiskat Kimberlites
Victor Diamond Prospect

Figure 13.1. A map highlighting the distribution of diabase dike swarms under Paleozoic cover of the James Bay Lowlands and the spatial correlation with kimberlite pipes. Early Jurassic kimberlite pipes, the Attawapiskat kimberlites, including the Victor diamond deposit, concentrate in a train parallel to one of a group of northwest-striking Matachewan (2446 Ma) diabase dikes and associated fractures. Mesoproterozoic (1100 Ma) kimberlite pipes, the Kyle kimberlites, are spatially concentrated near individual diabase dikes in a group of north-striking Marathon (2121 Ma) dikes. Kimberlite locations from Sage (1997); diabase dikes interpreted from Gupta (1991).

DIKE SWARMS

The following is a brief summary of dike swarms relevant to the present study. A study of more than 400 dikes of the giant Matachewan dike swarm (2446 to 2473 Ma: Heaman 1997) has demonstrated 1) the presence of new crustal blocks associated with the southwestern end of the Kapuskasing Structural Zone (KSZ); 2) that the level of crust exposed in the Superior Province both within and adjoining the KSZ gradually shallows toward the south, where it is ultimately underlain by Huronian volcanic rocks that may be part of the Matachewan magmatic event; and 3) that the Superior Province west of the KSZ has been rotated about 10 to 20° clockwise with respect to the Superior Province east of the KSZ with perhaps important implications for the origin of the Hudson Bay embayment (Bates and Halls 1991; Halls and Zhang 1998, 2002; Zhang 1999).

A paleomagnetic comparison of Biscotasing dikes (2170 Ma) across the KSZ gives a similar result (Halls and Davis 2002). The age of the deformation can only be placed between about 1885 and 2040 Ma. Other dike swarms remain to be tested, such as the Marathon swarm (2101 and 2121 Ma) and the Fort Frances dikes (2076 Ma) around the northern shore region of Lake Superior. Therefore, comparisons between dike swarms of 2 different ages across the KSZ show relative rotations between the western and eastern halves of the Superior Province and that the main zone of movement is along the KSZ. However, the deformation zone may be much broader and extend west from the KSZ for about 400 km (Manson and Halls 1997). This deformation within the western half of the Superior Province may be detectable because early paleomagnetic data suggested a progressive change in magnetic remanence declination with dike trend consistent with an increasing counterclockwise rotation of the western shield westwards from the KSZ. To this end, a major paleomagnetic and U/Pb geochronologic survey of northeast- and north-striking dikes is being carried out from the Kapuskasing Structural Zone in the east to Lake Nipigon in the west, in collaboration with D. Davis of the Jack Satterly Geochronology Laboratory, Royal Ontario Museum, Toronto. The dikes are known as the White River swarm in the west (Ernst and Halls 1984) and as the Kapuskasing dikes in the east (Halls and Palmer 1990). While some of the dikes are known to be Biscotasing age (Halls and Davis 2002), others may belong to the Marathon swarm, or may be associated with Keweenawan Nipigon sill activity, or could represent an entirely new swarm.

Buchan, Halls and Mortensen (1996) and Hamilton et al. (2002) have provided clearer documentation of the Marathon dike swarm north of Lake Superior since the summary and compilation by Osmani (1991). This swarm consists of north-striking dikes, largely concentrated between Lake Nipigon and Marathon. It is separated into 2 subsets characterized by normal and reverse paleomagnetic poles, respectively dated at 2121 Ma and 2101 Ma (Hamilton et al. 2002). This swarm overlaps an area east of Lake Nipigon where potential dikes associated with Keweenawan sills (1109 Ma) may occur.

FIELD WORK

In the summer of 2002, oriented samples were obtained from both chilled margins and interiors of dikes occurring between Lake Nipigon and Longlac (Table 13.1; Figures 13.2 and 13.3). A portable field drill was used to obtain cores, but block samples for later coring in the laboratory were also collected, particularly from the more densely fractured chilled margins. All samples were oriented using both sun and magnetic compasses (Photo 13.1) and locations were all obtained using a global positioning system. A total of approximately 150 samples were obtained from 10 paleomagnetic sites in northwest-striking dikes suspected to be Matachewan in age, and a further 4 sites from north- to northeast-striking dikes of unknown affinity. Preliminary paleomagnetic results on the northwest-striking dikes show clear primary remanence directions, typical of Matachewan dikes, with declinations generally between 180 and 200°, similar to those obtained previously from the Hornepayne and Ogoki Lake regions (Bates and Halls 1991).

Table 13.1. Locations of diabase dike samples for paleomagnetic and geochemical analysis; N = number of oriented samples collected.

Site Number	N	Location (Latitude °N, Longitude °W)	Dike Trend	Dike Width (m)
LL1	9	49°48.238′ , 86°33.078′	285°	40
LL2	10	49°44.692′ , 86°47.077′	290°	35
LL3	13	49°47.200′ , 86°34.600′	320°	20
LL4	6	49°40.930′ , 86°40.249′	NW	>20
LL5	11	49°47.919′ , 86°46.071′	315°	>40
LL6	7	49°47.487′ , 86°42.084′	295°	5
LL7	11	49°56.039′ , 86°48.595′	300°	3 dikelets
LL8	10	49°42.432′ , 87°22.376′	285°	25
LL9	5	50°8.590′ , 87°39.958′	308	25
LL10	10	50°9.959′ , 87°39.477′	295°	25
LL11	9	50°17.339′ , 87°31.728′	305°	10

All the above dikes were found to be paleomagnetically Matachewan, except LL7, which appears to have a younger Marathon(?) signature, and LL9, which gave poor results, possibly because the diabase was altered and Archean in age.

DP1	12	50°19.462′ , 87°1.218′	045°	60
DP2	6	49°48.209′ , 87°34.524′	015°	38
DP3	7	49°48.842′ , 87°38.901′	010°	27
DP4	8	49°27.567′ , 85°37.374′	040°	~120

These dikes are all suspected to be Marathon or Biscotasing, although Keweenawan (Nipigon) cannot yet be ruled out.

Photo 13.1. H.C. Halls orienting a drill core sample to be used for paleomagnetic analysis; from a Matachewan diabase dike on the Kinghorn Road in the Onaman–Tashota terrane.

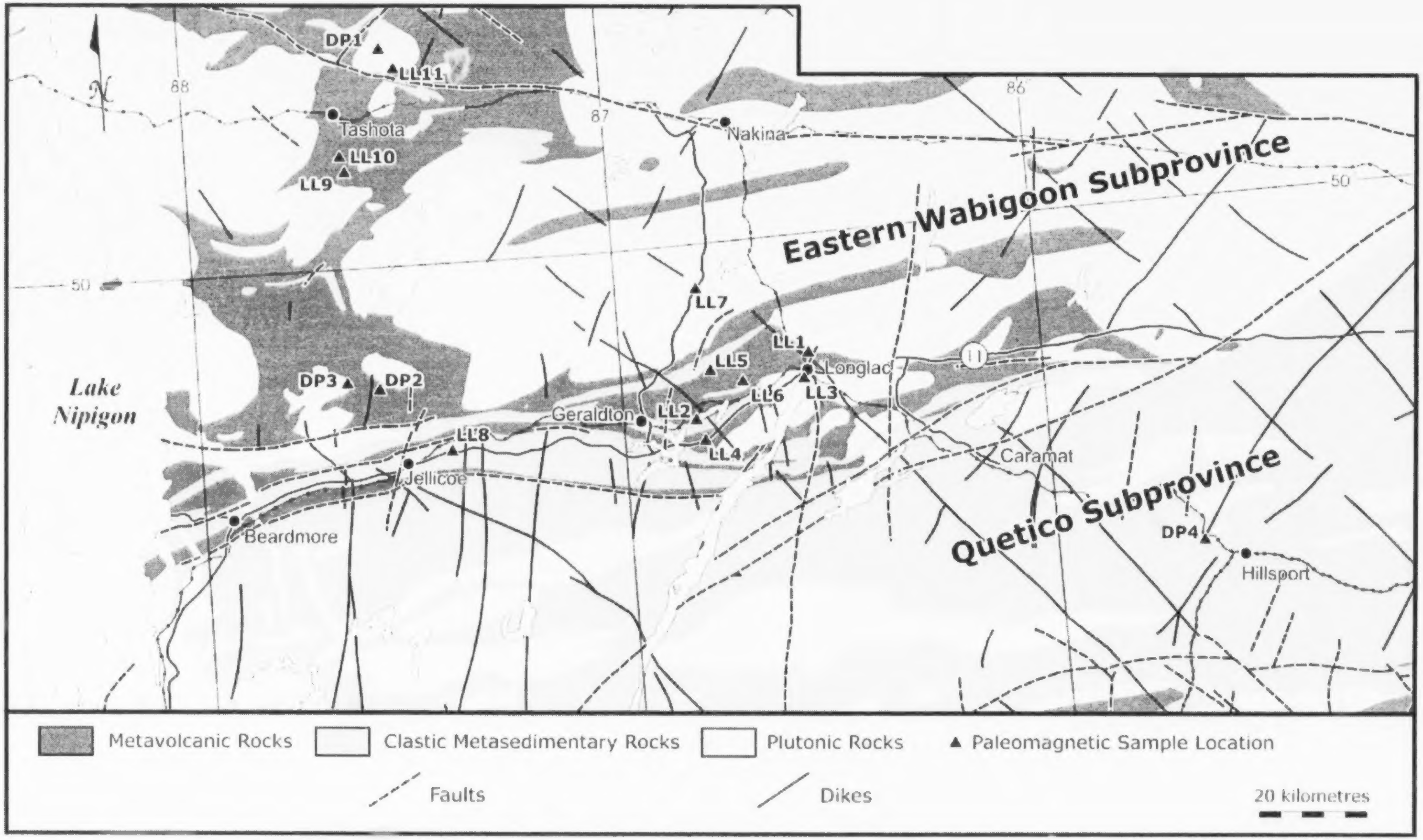
N
88
87
86
50
50
Lake Nipigon
DP1
LL11
Tashota
LL10
LL9
Nakina
Eastern Wabigoon Subprovince
LL7
LL1
Longlac
11
LL5
LL6
LL3
DP3
DP2
Geraldton
LL2
LL4
LL8
Jellicoe
Caramat
Beardmore
Quetico Subprovince
DP4
Hillsport
Metavolcanic Rocks
Clastic Metasedimentary Rocks
Plutonic Rocks
▲ Paleomagnetic Sample Location
Faults
Dikes
20 kilometres

Figure 13.2. Locations of Proterozoic diabase dikes sampled for paleomagnetic analyses between Lake Nipigon and Hillsport.

ECONOMIC CONSIDERATIONS

As Structural Controls of Kimberlite Emplacement

A geological interpretation, from regional airborne geophysical magnetic maps, of the Precambrian and Proterozoic basement underlying Phanerozoic cover in the James Bay and Hudson Bay Lowlands is being conducted by the senior author. This analysis includes identification of the various Proterozoic diabase dike swarms in that region. This work suggests that there is a correlation between 2 kimberlite pipe clusters and 2 diabase dike swarms. The early Jurassic pipes, including De Beers Canada Exploration Inc.'s Victor deposit (*see* Figure 13.1), mainly occur in a linear northwest trend close to a Matachewan (ca. 2446 Ma) diabase dike near the Attawapiskat River. This dike is part of a parallel group of northwest-

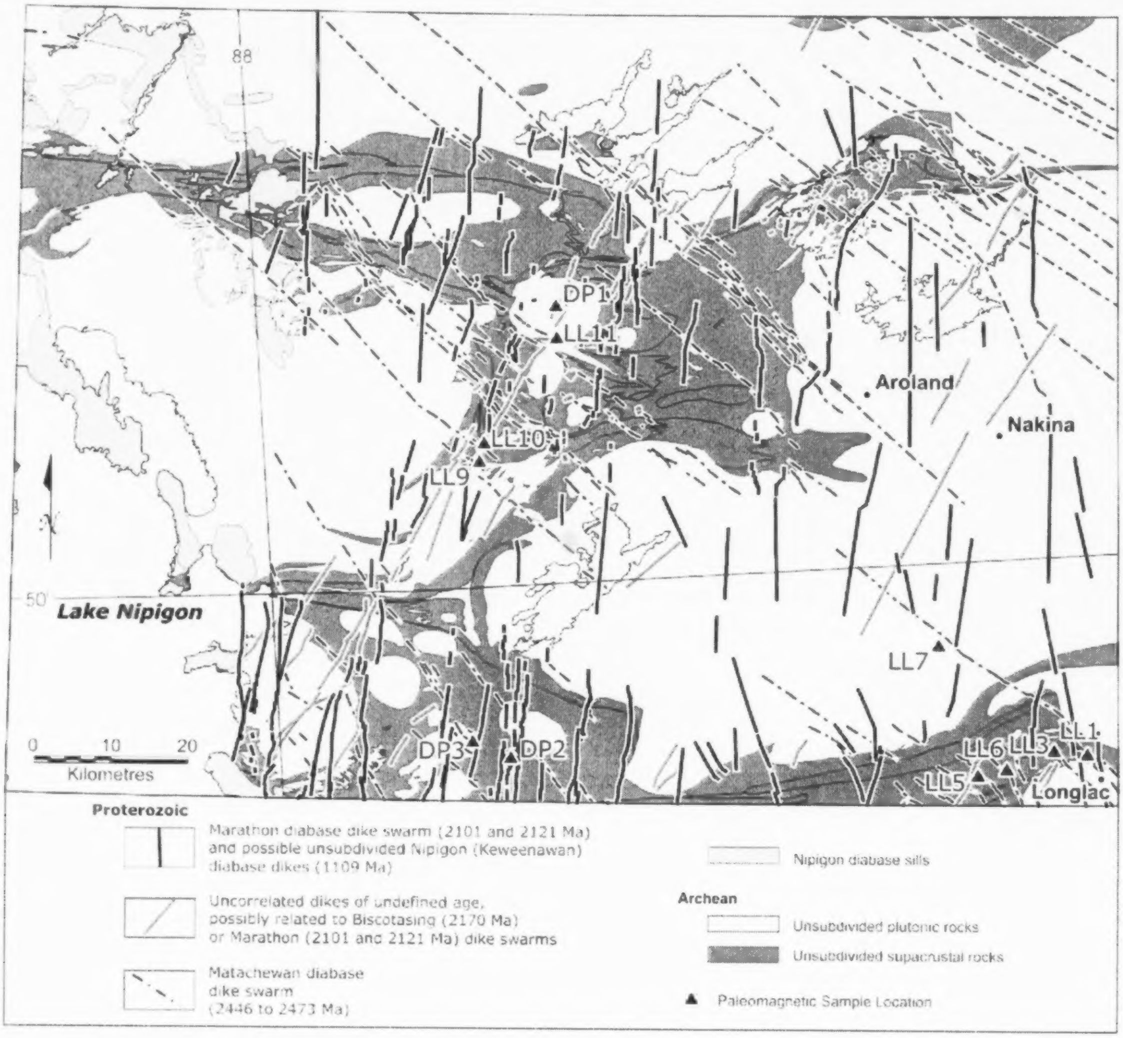
88
DP1
LL11
Aroland
Nakina
LL10
LL9
50
Lake Nipigon
LL7
0 10 20
Kilometres
DP3
DP2
LL6
LL3
LL1
LL5
Longlac
Proterozoic
Marathon diabase dike swarm (2101 and 2121 Ma) and possible unsubdivided Nipigon (Keweenawan) diabase dikes (1109 Ma)
Uncorrelated dikes of undefined age, possibly related to Biscotasing (2170 Ma) or Marathon (2101 and 2121 Ma) dike swarms
Matachewan diabase dike swarm (2446 to 2473 Ma)
Nipigon diabase sills
Archean
Unsubdivided plutonic rocks
Unsubdivided supracrustal rocks
Paleomagnetic Sample Location

Figure 13.3. A map of the Onaman–Tashota terrane, east of Lake Nipigon showing orientations of the diabase dike swarms being investigated and the locations of oriented dike samples obtained in this area.

striking dikes across an approximately 20 km width transected by the Winisk fault. It is suggested here that the deep crustal fractures associated with these dikes, arising from the giant Matachewan magmatic event, were reopened during subsequent episodes of displacement along the Winisk fault. Over 90 km farther west, the Marathon swarm (2121 Ma) forms an approximately 20 km wide group of dikes striking north in the vicinity of the Kyle kimberlite pipes (*see* Figure 13.1). Aeromagnetic maps indicate that these individual pipes occur in close proximity to linear magnetic anomalies that represent the trace of the dikes. The occurrence of both sets of kimberlite pipes, close to but generally not on the Winisk fault, implies the possibility that dike-associated fracture swarms served as second-order, extensional "splays" near this major fault and provided preferred emplacement pathways for pipe intrusions.

Approximately 60 to 80 km farther east of the Victor deposit, there is an overlap of another set of Matachewan and Marathon dike groups transected by the east-striking Winisk fault, where kimberlite pipes have not yet been discovered. This area might serve as an exploration test of this apparent correlation between kimberlite pipe intrusions and dike and fracture swarms, especially in proximity to the Winisk fault. It is to be expected that the aeromagnetic expression of some pipes might be masked by the presence of nearby dikes. This is a testable hypothesis and further research requires determining ages for fracture materials in these diabase–fracture swarms. The apparent correspondence between kimberlite pipe emplacements and aeromagnetically traceable groups of diabase dikes and accompanying fractures provides a potentially important structural control, especially where subjected to reactivated tensile stress near major transcurrent faults.

It is interesting to speculate that the giant Matachewan magmatic event might have played an indirect role both in serving as an anomalous source of nickel-copper-PGE mineralization under the Sudbury meteorite impact site, where similar ages of intrusions and the locus of the dike swarm are concentrated, and also in providing a fracture system used by early Jurassic kimberlite pipes in the Lowlands.

As Nickel-Copper-Platinum Group Element Targets

Prospectors have identified massive sulphide mineralization within diabase dikes in the Geraldton–Longlac region. For example, Mr. O. Albert, a prospector from Longlac, has a copper-nickel prospect in a north-trending diabase dike located southeast of Longlac, which Sherritt–Gordon Mines optioned in 1970 and conducted a multiphase exploration program. Mr. R. Coté, another prospector from Beardmore, discovered a large float of a diabase dike, between Longlac and Geraldton on the Camp 25 Road, with Cu (chalcopyrite)-Ni-PGE values (>1 g), but no mineralization has been found in place (J. Mason, Regional Resident Geologist – Thunder Bay North, personal communication, 2002). The association of such mineralization with a specific dike swarm has not been established, although Buchan, Halls and Mortensen (1996) have shown that north-striking dikes near Longlac are predominantly Marathon dikes with normal magnetic polarity (the 2121 Ma set) with few Marathon dikes of reverse magnetic polarity (the 2101 Ma set; Hamilton et al. 2002).

As An Industrial Commodity

One paleomagnetic site (DP 4) was obtained from a 100 m wide, northeast-striking dike at Hillsport (*see* Figure 13.2) (Milne 1964), which is presently being quarried for railroad ballast. Other correlative dikes of similar width and lithology (dense, abrasion-resistant and freeze–thaw resistant) may be exploitable for railroad ballast. It remains to be demonstrated that the widely separated northeast-striking Biscotasing dikes, of which the Hillsport dike is an example, are typically wider than dikes of other swarms and have greater potential for economically viable quarries near railways.

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14. Project Unit 95-014. Geology of the Upsala Area, South-Central Wabigoon Subprovince

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INTRODUCTION

The central Wabigoon Subprovince, located in the Ignace–Atikokan area of northwestern Ontario, is a key area for understanding the tectonic evolution and metallogeny of the western Superior Province. Underlain by Archean greenstone belts and a compositional spectrum of intrusive rocks, the central Wabigoon Subprovince has long been known to contain rocks of divergent age (Davis and Jackson 1988; Blackburn et al. 1991). These include a Mesoarchean (2.9 to 3.4 Ga) tonalite-greenstone complex near Atikokan and Neoarchean (2.5 to 2.9 Ga) granite batholiths and volcanic strata such as at White Otter Lake and in the Garden Lake greenstone belt (Figure 14.1). Further, the area holds a wide range of mineral resources including historic iron mines, shear zone-related gold, volcanogenic base metals, platinum group metals in mafic intrusions and rare metal pegmatites.

Geologic mapping was initiated in 1995 to study the origin and relationships between Mesoarchean and Neoarchean rocks as well as to examine regional controls on mineralization. The mapping has been used as a basis for U/Pb geochronologic and neodymium isotopic studies leading to definition of crustal blocks in the central Wabigoon Subprovince (Tomlinson et al. in press). The blocks include the Marmion terrane (2.93 to 3.0 Ga), which extends from west of Steep Rock Lake through Marmion and Lumby lakes to the area of the Heaven Lake greenstone belt (*see* Figure 14.1). Westward, the Marmion terrane lies in fault contact with oceanic Neoarchean greenstone belts and plutons of the western Wabigoon terrane. Lavas of the Garden Lake greenstone belt and plutons north of Ignace have Neoarchean ages, but complex negative ε_{Nd} values. These data have been interpreted by Tomlinson et al. (in press) to indicate that the magmas intruded through and assimilated older crustal material comparable in age to rocks of the Winnipeg River terrane. Accordingly, the area north of the Garden Lake greenstone belt is thought to represent the assimilated margin of the Winnipeg River terrane. Resulting from this terrane analysis is the interpretation that the central Wabigoon Subprovince is a collage of tectonically amalgamated crustal blocks.

In the current field season, mapping was extended east into the Upsala area (*see* Figure 14.1). This report summarizes the main observations on the geology, mineral potential and regional structural analysis that result from the new field work.

GEOLOGY

The Upsala area is situated approximately 110 km northwest of Thunder Bay, Ontario. The area is accessible by Highway 17 and a network of logging roads.

Previous mapping in the Upsala area includes regional surveys of Sage et al. (1974a, 1974b) and detailed investigations of part of the eastern Lumby Lake belt by Wolverton (1960) and Jackson (1985a). Milne (1964) and Hart et al. (2000) mapped the western Garden Lake belt that extends into the present area.

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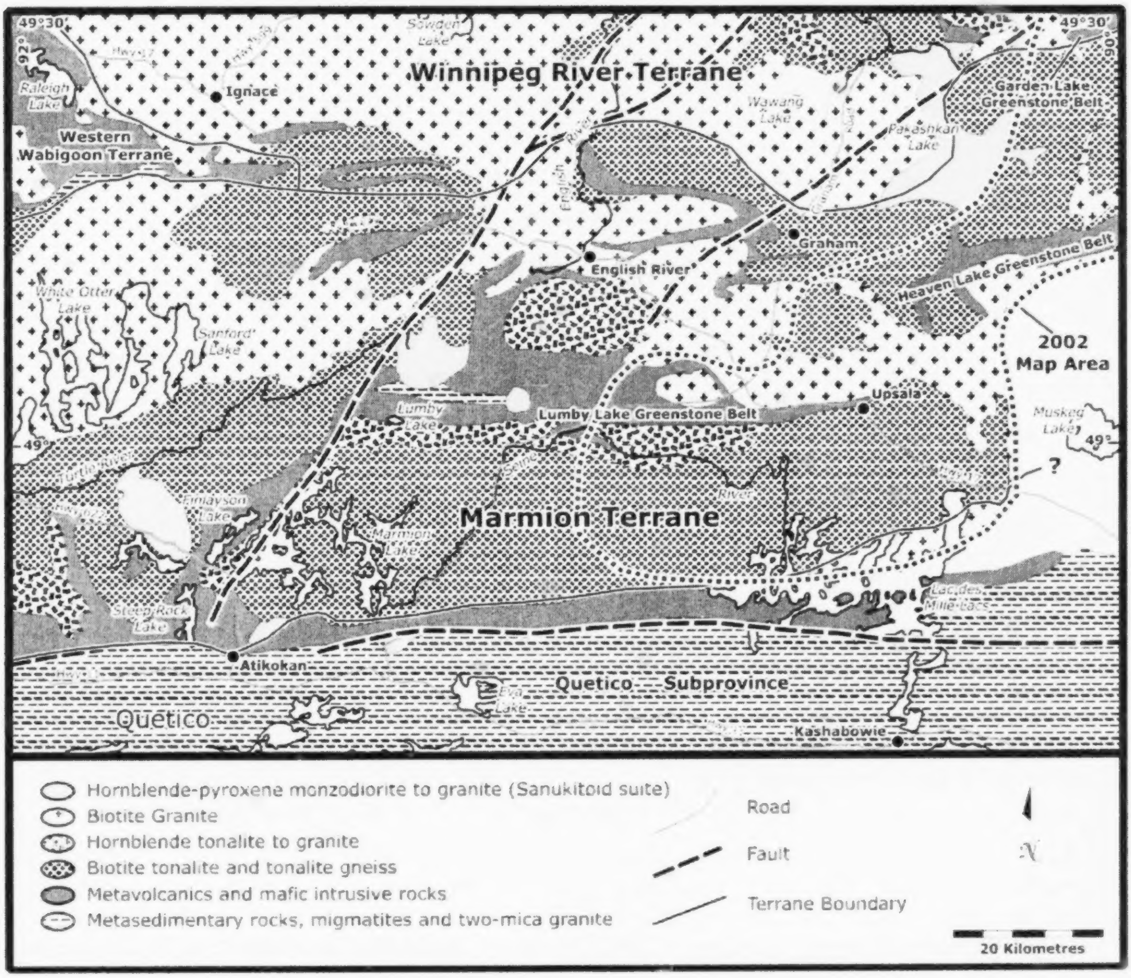
The Upsala area is underlain by parts of 3 Archean greenstone belts interspersed with relatively more voluminous plutonic domains. The greenstone belts, shown in Figures 14.1 and 14.2, include the eastern Lumby Lake belt (Treewartha–Hay lakes area), the western Garden Lake belt (northeast of Grew Lake) and the western Heaven Lake belt (Mirage–Muise–Herbert lakes area). The plutonic domains are subdivided into 6 major suites of felsic to intermediate intrusive and gneissic rocks, including biotite tonalite, tonalite gneiss, biotite granite, hornblende tonalite, clinopyroxene monzodiorite to granite and biotite + muscovite granite.

Lumby Lake Greenstone Belt

The eastern Lumby Lake greenstone belt attains a maximum width of 10 km south of Pyramid Lake and tapers eastward through Hay Lake (*see* Figure 14.2). Composed predominantly of metamorphosed basalt and associated gabbro with minor units of felsic metavolcanic and metasedimentary rocks, the eastern Lumby Lake greenstone belt is intruded internally by 2 oval plutons of biotite granite and externally by hornblende tonalite and biotite granite. The eastern end of the Lumby Lake greenstone belt



49°30'
92°
Hwy 17
Sowden Lake
Raleigh Lake
Ignace
Winnipeg River Terrane
Wawang Lake
49°30'
90°
Garden Lake Greenstone Belt
Western Wabigoon Terrane
Pakashkan Lake
English River
Graham
English River
Heaven Lake Greenstone Belt
White Otter Lake
Sanford Lake
2002 Map Area
Upsala
Lumby Lake
Lumby Lake Greenstone Belt
Muskeg Lake
49°
49°
Turtle River
Seine
River
?
Finlayson Lake
Marmion Terrane
Marmion Lake
Steep Rock Lake
Lac des Mille Lacs
Atikokan
Quetico Subprovince
Eva Lake
Quetico
Kashabowie
Hornblende-pyroxene monzodiorite to granite (Sanukitoid suite)
Biotite Granite
Hornblende tonalite to granite
Biotite tonalite and tonalite gneiss
Metavolcanics and mafic intrusive rocks
Metasedimentary rocks, migmatites and two-mica granite
Road
Fault
Terrane Boundary
N
20 Kilometres

Figure 14.1. Geology of the south-central Wabigoon Subprovince, northwestern Ontario.

is in contact with biotite tonalite, which may represent a basement complex on which the basaltic lavas erupted. The present mapping of the eastern Lumby Lake greenstone belt is summarized in Figure 14.3 and has defined significant new greenstone strata extending around the north side of the oval granite pluton at Treewartha Lake.

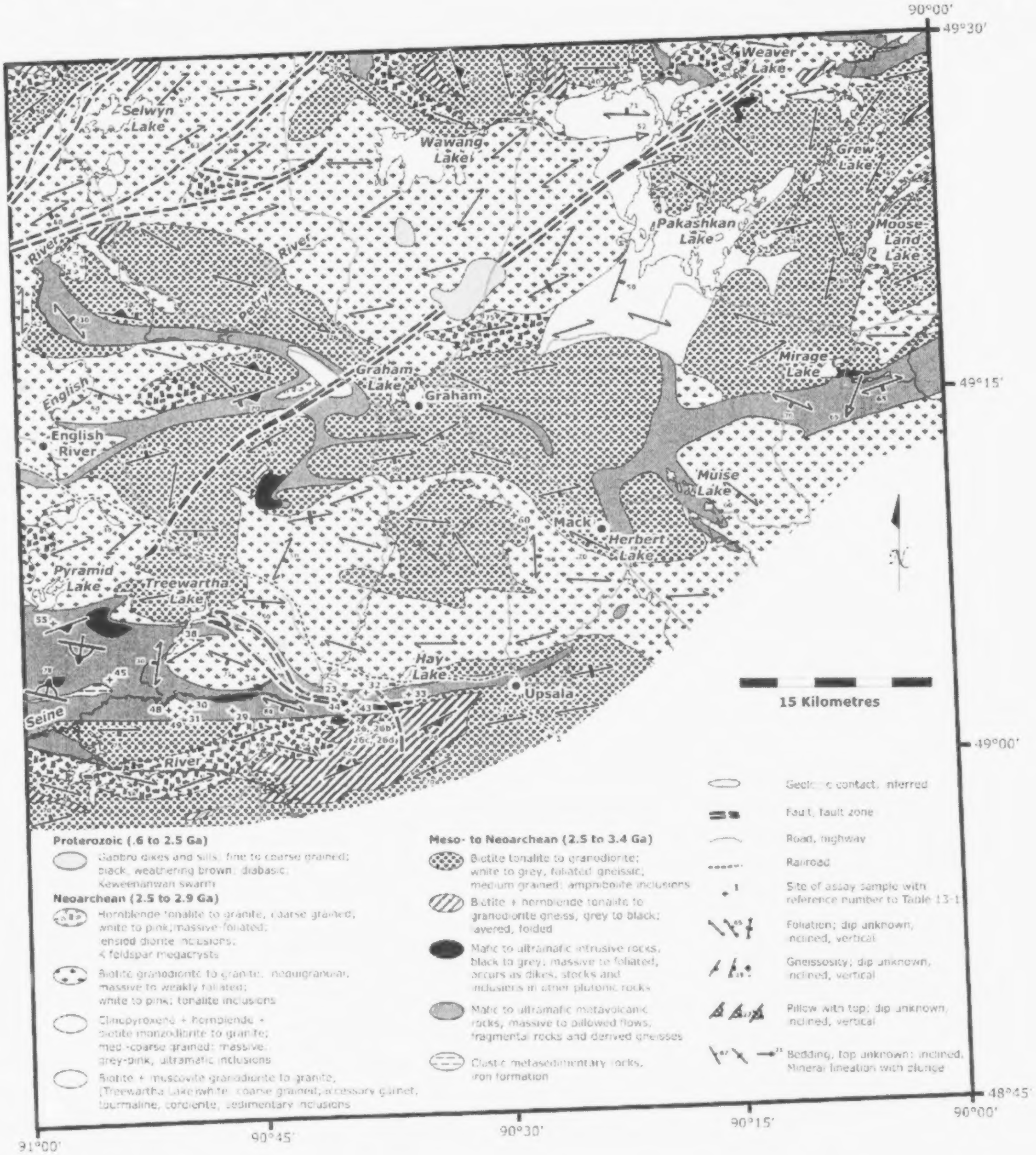

90°00'
49°30'
49°15'
49°00'
48°45'
91°00'
90°45'
90°30'
90°15'
90°00'
Selwyn Lake
Wawang Lake
Weaver Lake
Grew Lake
Pakashkan Lake
Moose Land Lake
River
Petry River
English River
Graham Lake
Graham
English River
Mirage Lake
Muise Lake
Mack
Herbert Lake
Pyramid Lake
Treewartha Lake
Hay Lake
Upsala
Seine River
N
15 Kilometres
Proterozoic (.6 to 2.5 Ga)
Gabbro dikes and sills; fine to coarse grained; black, weathering brown; diabasic; Keweenawan swarm
Neoarchean (2.5 to 2.9 Ga)
Hornblende tonalite to granite, coarse grained, white to pink; massive-foliated; ensiod diorite inclusions; K feldspar megacrysts
Biotite granodiorite to granite, inequigranular, massive to weakly foliated; white to pink; tonalite inclusions
Clinopyroxene + hornblende + biotite monzodiorite to granite; med.-coarse grained; massive; grey-pink, ultramafic inclusions
Biotite + muscovite granodiorite to granite, (Treewartha Lake) white, coarse grained; accessory garnet, tourmaline, cordierite, sedimentary inclusions
Meso- to Neoarchean (2.5 to 3.4 Ga)
Biotite tonalite to granodiorite; white to grey, foliated gneissic; medium grained; amphibolite inclusions
Biotite + hornblende tonalite to granodiorite gneiss, grey to black; layered, folded
Mafic to ultramafic intrusive rocks, black to grey; massive to foliated, occurs as dikes, stocks and inclusions in other plutonic rocks
Mafic to ultramafic metavolcanic rocks, massive to pillowed flows, fragmental rocks and derived gneisses
Clastic metasedimentary rocks, iron formation
Geologic contact, inferred
Fault, fault zone
Road, highway
Railroad
Site of assay sample with reference number to Table 13-1
Foliation; dip unknown, inclined, vertical
Gneissosity; dip unknown, inclined, vertical
Pillow with top; dip unknown, inclined, vertical
Bedding, top unknown; inclined, Mineral lineation with plunge

Figure 14.2. Geology of the Upsala area, northwest Ontario.

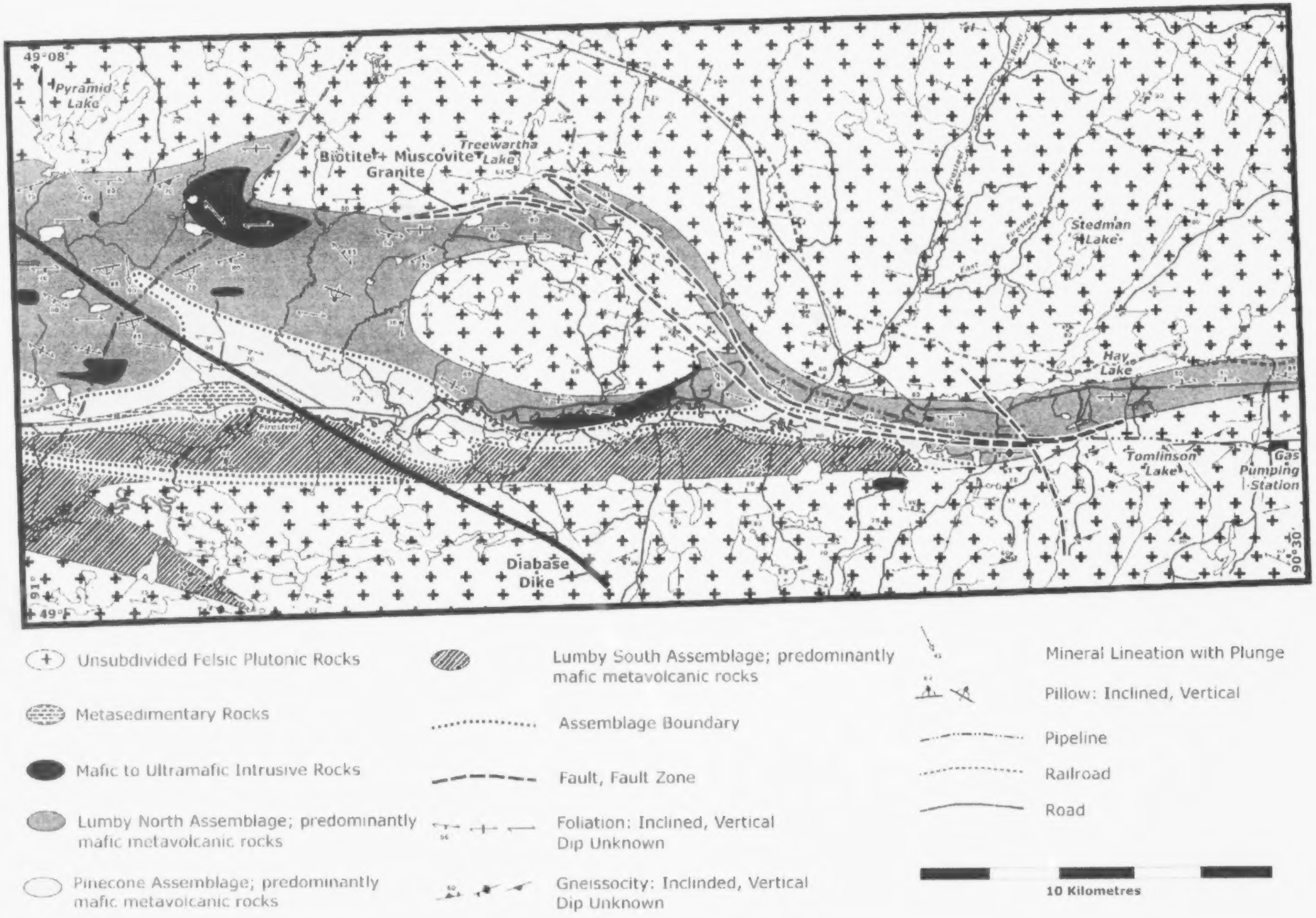

49°08'
Pyramid Lake
Biotite + Muscovite Granite
Treewartha Lake
Stedman Lake
Firesteel River
East Firesteel River
Hay Lake
Tomlinson Lake
Gas Pumping Station
Diabase Dike
91°
49°
90°30'
Unsubdivided Felsic Plutonic Rocks
Metasedimentary Rocks
Mafic to Ultramafic Intrusive Rocks
Lumby North Assemblage; predominantly mafic metavolcanic rocks
Pinecone Assemblage; predominantly mafic metavolcanic rocks
Lumby South Assemblage; predominantly mafic metavolcanic rocks
Assemblage Boundary
Fault, Fault Zone
Foliation: Inclined, Vertical Dip Unknown
Gneissocity: Inclinded, Vertical Dip Unknown
Mineral Lineation with Plunge
Pillow: Inclined, Vertical
Pipeline
Railroad
Road
10 Kilometres

Figure 14.3. Geology of the eastern Lumby Lake greenstone belt.

Table 14.1. Assemblages of the Lumby Lake greenstone belt.

Assemblage Name	Rock Type	Age (Ma)*	Tectonic Setting
Lumby North	Basalt, gabbro, minor rhyolite	3013.6±1.3 2963.3±4.5	Continental plume-related
Lumby South	Basalt, gabbro, dacite and rhyolite	3001.1±1.1 2999.4±2.9 2999.1±2	Volcanic arc
Pinecone	Basalt, komatiite	2828.3±1.8	Continental plume-related
Bar	Basalt, minor felsic tuff	2897.6±2.1	Unknown
Unnamed sedimentary	Sandstone, conglomerate, local siltstone, iron formation and marble	unknown	Possible continental platform

* Ages are *from* Davis and Jackson (1988); Tomlinson et al. (1999, in press).

The well-exposed western Lumby Lake greenstone belt (west of the present area) has been subdivided into 5 assemblages, listed in Table 14.1, on the basis of extensive mapping, geochronological, geochemical and isotope studies (e.g., Jackson 1985a, 1985b; Davis and Jackson 1988; Tomlinson et al., in press). Four of these assemblages have been traced eastward into the present area as shown in Figure 14.3. The Lumby North assemblage represents the northern half of the greenstone belt and is composed of pillowed basalt flows with a high proportion of massive flows and gabbro and minor felsic volcanic units. These strata are metamorphosed to amphibolite facies. A thin arkosic unit separates mafic lavas from tonalite at Treewartha Lake and possibly represents a platform sequence. Arkosic beds and pyritic iron formation units are interlayered with mafic lava flows at the eastern end of the belt at Hay Lake. The arkosic units provide an indication that the basaltic lavas were erupted onto continental crust and were interbedded with clastic detritus derived from adjacent highlands. The continental basement is possibly represented by biotite tonalite and tonalite gneiss, which are in contact with the eastern margins of the belt (*see* Figure 14.2). High strain has precluded identification of an unconformity at this locality.

The Lumby South assemblage is composed of highly strained and metamorphosed massive and pillowed basalts in thin (1 to 2 km wide) units at the south side of the Lumby Lake greenstone belt. Although intermediate to felsic volcanic rocks are common in this assemblage to the west, these rocks comprise only a few percent of the South Lumby assemblage in the present area. The Lumby South assemblage is intruded by hornblende tonalite at the south side of the belt.

The Pinecone assemblage is characterized by mafic lava flows with rare units of komatiite and felsic volcanic rocks. A low grade of metamorphism, represented by green basalts with mineral assemblages of chlorite + epidote ± actinolite, is a distinguishing field characteristic of the Pinecone assemblage in contrast with black hornblende in the more highly metamorphosed Lumby North and Lumby South assemblages. The Pinecone assemblage occupies thin (up to 3 km wide) and variably bifurcated units in the south-central Lumby Lake greenstone belt.

Although well exposed along the central axis of the western Lumby Lake greenstone belt, metasedimentary rocks are rare in the present area. A few outcrops of slate and cherty iron formation are interpreted to represent an unnamed sedimentary assemblage that appears to be surrounded by the Pinecone assemblage in the western part of the area (*see* Figure 14.3). The sedimentary assemblage is distinguished by a strong magnetic anomaly on aeromagnetic maps (e.g., OGS 1980a).

A broad fault zone extends southeasterly from Treewartha Lake (*see* Figure 14.3) through metasedimentary rocks, an oval biotite granite pluton and parts of the Lumby North and Pinecone assemblages. The fault zone at Treewartha Lake contains migmatized arkosic sandstone. A narrow unit of biotite + muscovite granite is developed adjacent to the metasedimentary rocks. Farther southeast, faulted biotite granite shows a prominent mylonitic texture and actinolite and sericite + carbonate schists are developed in faulted volcanic strata. A late, brittle, sinistral fault at the west end of Hay Lake offsets the Lumby Lake greenstone belt by a few hundred metres.

Garden Lake Greenstone Belt

The Garden Lake greenstone belt is an east-trending, south-facing sequence of dominantly mafic metavolcanic rocks (Hart 1999; Hart et al. 2000) that extends 8 km into the northeast corner of the area (*see* Figure 14.2). Thin units (up to 15 m wide) of felsic tuff are interbedded with mafic flows at the southwest end of the belt and an age of 2725.5±1.3 Ma has been determined (Tomlinson et al., in press). The felsic tuffs have an ε_{Nd} value of –2.40 and 3.2 Ga model age, which is interpreted to indicate that the magmas of the Garden Lake belt erupted through and assimilated older crust comparable to the Winnipeg River terrane (Tomlinson et al., in press).

The Garden Lake greenstone belt is intruded by biotite granite at its western terminus. Several greenstone slivers within plutonic rocks in the area of Weaver Lake (*see* Figure 14.2) are possibly fragments of the Garden Lake greenstone belt.

Heaven Lake Greenstone Belt

The Heaven Lake greenstone belt is dominated by mafic metavolcanic flows and associated gabbro and attains a maximum width of 5 km (*see* Figures 14.1 and 14.2). West of Mirage Lake, the Heaven Lake greenstone belt is completely covered by surficial materials and is interpreted to bifurcate into 3 north- to northwest-trending arms (*see* Figure 14.2) on the basis of magnetic patterns on aeromagnetic maps (ODM–GSC 1965). Where exposed south of Mirage Lake, strata of the Heaven Lake greenstone belt are strongly foliated, metamorphosed to amphibolite facies and dip steeply to the south. Rare cherty and sulphide-facies iron formation is interlayered with the mafic lava flows. Sage et al. (1974b) has interpreted strong magnetic anomalies at Herbert Lake and Muise Lake to represent gabbro intrusions associated with the greenstone belt.

Hart and MacDonald (2000) subdivided the eastern Heaven Lake greenstone belt (30 km east of the present area) into the Whitton and Whistle assemblages. The Whitton assemblage is composed of mafic metavolcanic flows with minor intermediate tuffs capped by komatiite, iron formation and marble. Tuffs of the Whitton assemblage have yielded an age of 2957.7±1.3 Ma (Tomlinson et al., in press). The Whistle assemblage is restricted to the easternmost part of the belt and consists of intermediate tuffs for which an age of 2729±2 Ma has been obtained (Tomlinson et al., in press).

Based on similar mafic-dominated lithologies and on-strike distribution, the metavolcanic sequences in the Mirage Lake area are interpreted to be the western extension of the Whitton assemblage.

INTRUSIVE ROCKS

Biotite Tonalite Suite

Plutonic rocks of the biotite tonalite suite are typically medium to coarse grained, white to grey and variably foliated ranging from tonalite to granodiorite in composition. Crosscutting relations show that the biotite tonalite suite is locally among the oldest plutonic suites. It occurs widely in the Upsala area as large masses of oval to variably tapered and belt-like form such as south of Hay Lake and at Graham and Grew lakes (*see* Figure 14.2). Biotite tonalite, south of the Lumby Lake greenstone belt at Hay Lake, is part of the eastern Marmion batholith from which a mafic tonalite enclave at Steep Rock Lake has yielded an age of 3001.6 +3.4/–2.3 Ma (Tomlinson et al., in press).

Tonalite Gneiss Suite

Tonalite gneisses are heterogeneous layered rocks commonly made up of several compositional or textural varieties of biotite tonalite and granodiorite as well as diorite and amphibolite. Tonalite gneisses occur in the Marmion batholith south of Hay Lake and as small units at scattered localities typically associated with biotite tonalite (*see* Figure 14.2). An age of 3003±3 Ma has been obtained from the gneissic phases of the Marmion batholith (Tomlinson et al., in press).

Hornblende Tonalite Suite

Hornblende tonalite grades compositionally to granodiorite and is a coarse, granular and foliated mesocratic rock with 10 to 30% biotite and hornblende. The hornblende tonalite suite occurs at the south margin of the Lumby Lake greenstone belt and as small units at scattered localities (*see* Figure 14.2). Although crosscutting relations show that hornblende tonalite predates the biotite granite suite (discussed below), age relations with biotite tonalite are unclear.

Biotite + Muscovite (Peraluminous) Granite Suite

Although rare in the Upsala area, biotite + muscovite granite occurs as scattered dikes in supracrustal and plutonic rocks and as a small unit at the north margin of the Lumby Lake greenstone belt at Treewartha Lake (*see* Figure 14.3). Biotite + muscovite granite is coarse grained and white and may contain accessory garnet, tourmaline and cordierite. The unit at Treewartha Lake is associated with clastic metasedimentary rocks and shows protomylonitic texture.

Biotite Granite Suite

Biotite granodiorite to granite is typically coarse grained, leucocratic and white to pink showing a weak fabric and containing inclusions of older rocks such as biotite tonalite. The suite occurs widely in the Upsala area in forms ranging from dikes through oval stocks and plutons to large batholiths (*see* Figure 14.2). Biotite granite with large (up to 50 mm) potassium feldspar megacrysts occurs east and northeast of Upsala.

Clinopyroxene + Hornblende Monzodiorite (Sanukitoid) Suite

The sanukitoid suite ranges compositionally from mafic to intermediate diorite, monzodiorite and monzonite to felsic granodiorite and granite. Clinopyroxene tends to predominant in mafic and quartz-undersaturated phases giving way to hornblende and biotite in felsic components of this suite. Sanukitoid intrusions occur as late oval plutons in the south-central Wabigoon Subprovince and include the large irregular body at Pakashkan Lake (*see* Figure 14.1).

Mafic Suite

Two categories of Archean mafic to ultramafic intrusive rocks are identified in the Upsala area. These include gabbro and diorite associated with mafic volcanic rocks and a compositional spectrum of hornblendite-gabbro-diorite intrusions that occur widely in both plutonic and supracrustal domains. The former intrusions occur as sills, dikes and irregular intrusions within mafic volcanic sequences and appear to have been emplaced coeval with mafic volcanism. Intrusions of this type are particularly common in the Lumby North assemblage (*see* Figure 14.3).

Hornblendite-gabbro-diorite intrusions occur as oval to irregular stocks, such as at Weaver Lake and southwest of Hay Lake (*see* Figures 14.2 and 14.3). These are composed predominantly of coarse massive hornblendite, which locally grades to more felsic phases including gabbro and diorite. Crosscutting relations indicate that hornblendite intrusions are relatively young intrusive rocks possibly comparable in age to the sanukitoid and biotite granite suites.

Diabase Suite

Massive brown-weathering gabbro showing diabasic texture occurs as dikes and sills in the Upsala area. The larger of these intrusions are marked by prominent aeromagnetic anomalies (ODM–GSC 1965). The diabase intrusions are interpreted to be part of the Proterozoic Wabigoon and Keweenawan dike swarms (Osmani 1991; Sutcliffe 1989).

ECONOMIC GEOLOGY

The Upsala area hosts a variety of mineral occurrences, including base metals, gold, platinum group metals and rare metals.

Base Metals

The Heaven Lake greenstone belt has been explored for base metals. Sage et al. (1974b) summarized results of extensive diamond drilling by Phelps Dodge Ltd. on geophysical targets. The diamond-drill holes intersected pyrite and pyrrhotite mineralization evidently associated with unexposed iron formation units in the mafic volcanic sequences. During the present survey, a boulder (approximately 0.5 m diameter) of massive sulphide minerals, possibly originating from metamorphosed iron formation, comparable to the drill targets, was found in the bed of a logging road southwest of Mirage Lake. A sample of the boulder, composed primarily of pyrite and pyrrhotite, contains 600 ppm Cu and 237 ppm Ni. Sage et al. (1974b) interpreted strong magnetic anomalies at Herbert Lake and Muise Lake (*see* Figure 14.2) to represent unexposed gabbro intrusions associated with the western Heaven Lake greenstone belt. These intrusions are potential sources of copper, nickel and platinum-group metal mineralization.

Table 14.2. Assays of rock samples from the Upsala area.

Sample[1]	Area	UTM East [2]	UTM North [2]	Rock	Au (ppb)[3]	Ag (ppm)[3]	Pt (ppb)[3]	Pd (ppb)[3]
1	Upsala	687408	5431680	gabbro	<5	2	<8	<8
23	W Upsala	671489	5435080	mafic volcanic	<5	3	<8	<8
26	W Upsala	670786	5433125	hornblendite	13.2	4	<8	<8
26b	W Upsala	671266	5433411	hornblendite	<5	3	<8	<8
26c	W Upsala	671124	5433384	hornblendite	<5	3	<8	<8
26d	W Upsala	670780	5433128	hornblendite	20.6	5	9.48	17.26
29	W Upsala	662599	5434564	diorite	<5	2	8.75	9.5
30	W Upsala	659183	5434325	monzonite	<5	1	<8	<8
31	W Upsala	658917	5434099	granite	<5	1	<8	<8
32	W Upsala	672823	5435403	quartz vein	<5	<1	<8	<8
33	W Upsala	676213	5434946	iron formation	<5	<1	<8	<8
34	S Treewartha L.	662641	5436198	quartz vein	<5	<1	<8	<8
38	S Treewartha L.	658612	5439798	epidote-ankerite alteration	<5	4	<8	<8
43	W Upsala	672100	5435137	gabbro	<5	4	<8	<8
44	W Upsala	671958	5434452	gabbro	<5	4	<8	<8
45	S Pyramid L.	654036	5435986	quartz vein	<5	3	<8	21.05
48	N of N Bedivere L.	657418	5434407	mafic volcanic	13.51	3	<8	<8
49	N of N Bedivere L.	657744	5434240	granite	<5	2	<8	13.22
55	S Pyramid L.	648229	5440966	gabbro	<5	3	<8	<8
60	N Upsala	684731	5449377	hornblendite	<5	3	<8	<8

[1] See sample locations on Figure 14.2.
[2] Universal Transverse Mercator co-ordinates are in metres, Zone 15, North American datum 1927
[3] Detection limits are: Au (5 ppb); Ag (1 ppm); Pt (8 ppb); Pd (8 ppb)

Thin intraflow sedimentary horizons are common in mafic volcanic sequences at Hay Lake in the eastern Lumby Lake greenstone belt. These rusty zones are composed of arkosic grit and chert and are mineralized with pyrite, pyrrhotite and rare chalcopyrite. Several rusty zones were sampled and analyses returned negligible values of gold and silver (e.g., samples 23, 32 and 33 of Table 14.2); base metal results are not yet available, but are expected to show low concentrations of copper. Occurrences of massive and disseminated pyrite were noted at scattered localities elsewhere in the Lumby Lake greenstone belt (e.g., samples 29, 45 and 55 of Table 14.2). The pyrite typically occurs with quartz veins and sheared volcanic rock. Samples of this material contain low concentrations of gold and silver (*see* Table 14.2).

Atikokan Resources Ltd. (www.atikokan.com) has recently defined copper-zinc-lead mineralization associated with felsic volcanic sequences in the Lumby South assemblage of the western Lumby Lake greenstone belt. Although the Lumby South assemblage is interpreted to extend eastward into the present area (*see* Figure 14.3), the felsic volcanic component of this assemblage diminishes eastward. Accordingly, the potential for base metal mineralization in this assemblage appears to be better in the west than in the east.

Gold

New mapping has defined a shear zone with potential for gold mineralization in the eastern Lumby Lake greenstone belt. The zone of high strain extends southeasterly from Treewartha Lake and cuts an oval biotite granite pluton and parts of the Lumby North and Pinecone assemblages west of Hay Lake (*see* Figure 14.3). The shear zone is marked by mylonite and a local stockwork of quartz veins within the biotite granite pluton. Actinolite schists and quartz veins are developed where the shear zone cuts the Lumby North assemblage and chlorite + carbonate + quartz schists occur in the faulted parts of the Pinecone assemblage. Development of quartz veins and carbonate alteration provide an indication that the shear zone has been a conduit for fluid movement with possible associated gold mineralization. The shear zone in considered an attractive target for gold exploration in the eastern Lumby Lake greenstone belt.

A small (2 km diameter) biotite granite plug has intruded greenschist-facies volcanic rocks interpreted as part of the Pinecone assemblage at the south side of the Firesteel River in the central Lumby Lake greenstone belt (*see* Figure 14.3). Outcrops of metavolcanic and plutonic rocks within the strained contact zone of this plug have been trenched, evidently in search of gold mineralization. During the present survey, several samples of sheared volcanic rock, granite and quartz veined material were collected from this locality, however, the samples yielded negligible gold values (samples 30, 31, 48 and 49 of Table 14.2).

Platinum Group Metals

Two hornblendite plugs located at Weaver Lake and 3 km southwest of Hay Lake (*see* Figure 14.2) have been defined by recent mapping and are potential sources of platinum group metals. Stone and Hallé (2000) reported an assay of 200 ppb combined Au+Pt+Pd from the Weaver Lake intrusion. Further work in the Weaver Lake area during the current field season showed that the Weaver Lake intrusion is poorly exposed, however, hornblendite boulders are common south of the body. Several boulders have been sampled.

The hornblendite plug southwest of Hay Lake has intruded gneisses at or near the south margin of the Lumby Lake greenstone belt. The poorly exposed ultramafic body has a strong aeromagnetic anomaly (OGS 1980b). Grab samples contain disseminated chalcopyrite and, although analyses reveal background levels of Au, Pt and Pd (*see* samples 26 to 26d of Table 14.2), further work is recommended to evaluate the mineral potential of this intrusion.

Rare Metal Pegmatites

Rare metals, such as beryllium, cesium, gallium, lithium, niobium, rubidium and tantalum, are typically found within accessory minerals, including beryl, columbite, spodumene, holmquistite and tantalite, associated with pegmatitic phases of the peraluminous granite suite (e.g., Breaks 1993). A 3 km long unit of coarse-grained, white, peraluminous granite was mapped at Treewartha Lake (*see* Figure 14.3) and provides an exploration target for rare metals. The unit needs to be prospected for pegmatitic phases containing rare-metal minerals.

SUMMARY

Regional surveys have provided updated geologic maps of the Firesteel River and Pakashkan Lake areas in the south-central Wabigoon Subprovince. The new mapping has shown that the eastern Lumby Lake greenstone belt is significantly larger than was previously known and has provided geologic data for the interpretation of assemblages, major structural features and gold exploration targets within the belt. Arkosic sediments interbedded with mafic lavas of the Lumby North assemblage provide evidence that this assemblage was erupted on submerged sialic material, perhaps represented by biotite tonalite and tonalite gneiss sequences of the Marmion batholith.

Within plutonic areas, ultramafic stocks with potential for mineralization by platinum group metals and peraluminous granite with an affinity for rare metal mineralization have been identified. Regionally, felsic plutonic areas are subdivided into biotite tonalite and tonalite gneiss suites possibly representative of Mesoarchean crust and hornblende tonalite, biotite granite and sanukitoid suites, which probably developed in the Neoarchean. Biotite tonalite and tonalite gneiss characteristic of the Marmion batholith have been traced from Marmion Lake to east of Lac des Mille Lacs where the Mesoarchean rocks are truncated by younger plutonic suites. Although further work is required in this area, the mapping implies that the contiguous Marmion terrane does not extend east of Lac des Mille Lacs. In contrast, large bodies of biotite tonalite have been mapped north and northeast of Lac des Mille Lacs such as at Graham Lake and Grew Lake. Although ages have not been determined for the tonalite and these units are separated from the Marmion batholith by younger intrusive suites, the tonalitic enclaves may comprise crustal fragments correlative with the Marmion batholith and provide an overall northeasterly trace for the 3000 million year old Marmion terrane. Alternatively, the tonalitic enclaves may represent one or more separate and presumably younger intrusive masses or exotic crustal fragments whose structural relation to the Marmion terrane is obscured by late biotite granite.

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15. Project Unit 02-008. Geology and Mineral Potential of Henry and Loughrin Townships, Grenville Province

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INTRODUCTION

Since 1998, the Paleoproterozoic River Valley intrusion has been the subject of extensive exploration for platinum group element and nickel-copper mineralization. To assist in this exploration effort, the Ontario Geological Survey mapped the better preserved eastern half of the River Valley intrusion in Dana and Crerar townships in 1999 (Easton and Hrominchuk 1999, 2001a, 2001b, 2002; Hrominchuk 1999, 2000). Mapping during the 2002 field season focussed on the more deformed western parts of the River Valley intrusion exposed in Henry and Loughrin townships (Figure 15.1), with the aim to better understand the original form, stratigraphy and mineral potential of this part of the River Valley intrusion. Mapping was conducted at 1:20 000 scale in areas underlain by rocks of the River Valley intrusion, and at 1:50 000 scale in the remainder of the map area. Mapping was ongoing as this report was being prepared, consequently, this report highlights only some of the preliminary mapping results from the field season.

PREVIOUS WORK

Mapping of the 2 townships at 1:63 360 scale was conducted in 1971 as part of a regional mapping program (Lumbers 1971, 1973), which indicated that the River Valley intrusion in Henry and Loughrin townships consisted of at least 3, east-northeast-trending linear belts (Figure 15.2). Prior to 1995, mineral exploration in the 2 townships had focussed on industrial minerals, namely garnet (Vos et al. 1981), feldspar (Vos et al. 1981) and building stone (WIFCo and Dallaire 1985, Kirwan 1992, Sawitzky 1994, Positano 1995). During 1995, WMC International Ltd. conducted mapping and geophysical surveys over Henry and Loughrin townships during a search for platinum group element and nickel-copper mineralization (Newman 1996). As part of the Operation Treasure Hunt program, proprietary airborne geophysical data collected by WMC International Ltd. in 1995 was released in March 2002 (Ontario Geological Survey 2002). Between 1998 and 2002, exploration for platinum group element and nickel-copper mineralization in the area has been conducted mainly by Aquiline Resources Inc., Mustang Minerals Corporation, and Platinum Group Metals and their subcontractors (e.g. Aquiline Resources Inc. 2000; Dimmell 2000; Haynch 2002; Haynch and Gore 2000; Wood 2002).

REGIONAL GEOLOGICAL SETTING

Henry and Loughrin townships lie solely within the Grenville Front tectonic zone of the Grenville Province (Easton 1992), however, the northeast corner of Loughrin Township and the northwest corner of Henry Township lie 1 km and 2 km south of the Grenville Front, respectively (*see* Figure 15.1). Country rocks to the River Valley intrusion are inferred to be mainly Archean in age, based on mapping in

Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.15-1 to 15-16.

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adjacent Street and Crerar townships (Easton 2000; Easton and Murphy 2002; Easton and Hrominchuk 2001a). Outcrop is most abundant (40 to 50% exposure) in northwest Loughrin Township and becomes sparser to the east and south (<15% exposure).

Two structural fabrics dominate the study area and are oriented roughly perpendicular to each other. Many rock units in the area show an east to east-northeast orientation, however, in many places, particularly in western Henry Township, the dominant penetrative fabric in the rock (generally gneissic layering) is oriented in a northerly direction at a high angle to the rock unit contacts. In many parts of the River Valley intrusion in northern Henry and Loughrin townships, 2 fabrics are observed. In some areas, the easterly fabric is earlier and cut by the northerly fabric, which commonly serves as a focus for local veining or leucosome development. In other areas, the northerly fabric appears to be earlier, and is crenulated by the easterly fabric. It is possible, however, that several generations of fabrics are present, which would explain these apparently contradictory relative-age relationships. The lack of a reliable stratigraphy in either the country rock or the River Valley intrusion make it difficult to map out large-scale folds within the map area, a process further complicated by the fact that rock unit contacts may have different trends than the measured penetrative fabrics within those rock units.

Metamorphic grade in the study area is upper amphibolite facies. Metasedimentary gneissic rocks in northwest Loughrin Township do not contain primary muscovite, and are sillimanite bearing, suggesting metamorphic conditions greater than muscovite breakdown. Country rocks to the River Valley intrusion, as well as felsic intrusive rocks in the area, are commonly migmatitic.

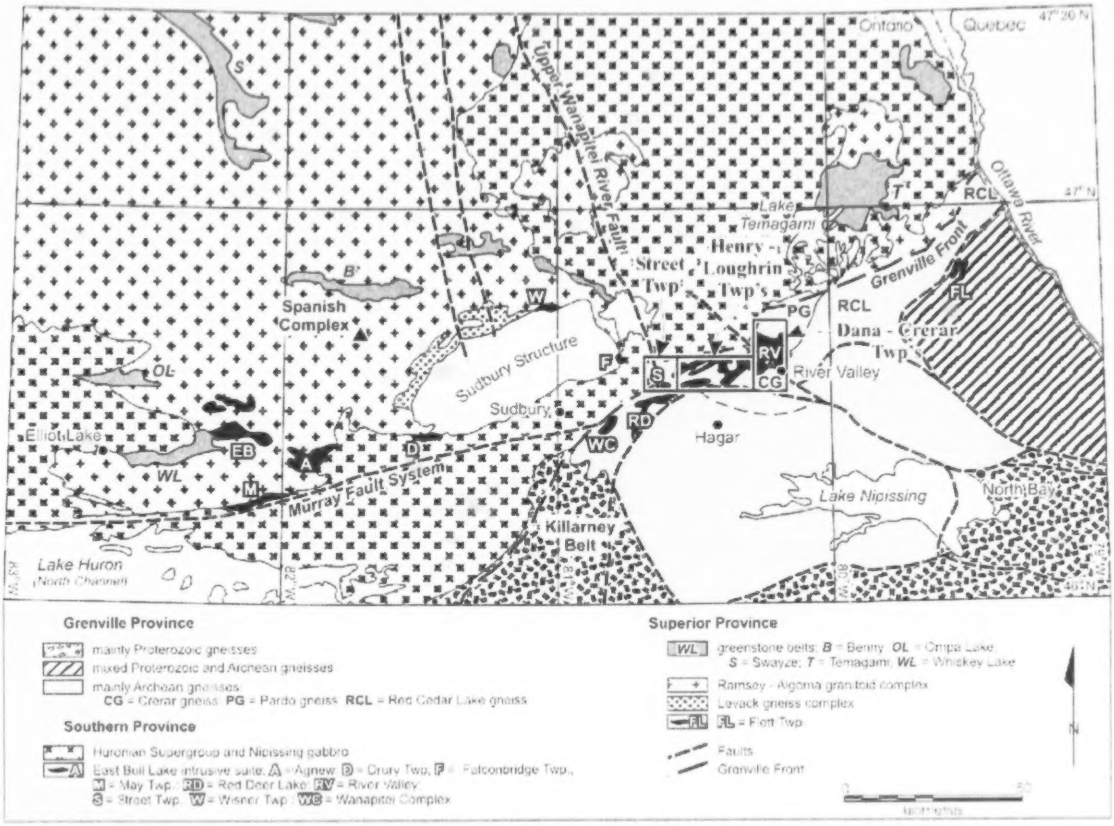
Ontario
Quebec
47°30'N
47°N
46°N
83°W
82°W
81°W
80°W
79°W
S
T
RCL
Ottawa River
Upper Wanapitei River Fault
Lake Temagami
Henry - Loughrin Twp's
Street Twp
Grenville Front
FL
B
W
Spanish Complex
PG
RCL
Dana - Crerar Twp's
Sudbury Structure
F
S
RV
CG
River Valley
OL
Sudbury
RD
Hagar
Elliot Lake
EB
D
A
WC
WL
M
Murray Fault System
Lake Nipissing
North Bay
Killarney Belt
Lake Huron
(North Channel)
Grenville Province
mainly Proterozoic gneisses
mixed Proterozoic and Archean gneisses
mainly Archean gneisses
CG = Crerar gneiss PG = Pardo gneiss RCL = Red Cedar Lake gneiss
Southern Province
Huronian Supergroup and Nipissing gabbro
East Bull Lake intrusive suite: A = Agnew; D = Drury Twp; F = Falconbridge Twp.,
M = May Twp.; RD = Red Deer Lake; RV = River Valley;
S = Street Twp.; W = Wisner Twp.; WC = Wanapitei Complex
Superior Province
WL greenstone belts: B = Benny; OL = Ompa Lake;
S = Swayze; T = Temagami; WL = Whiskey Lake
Ramsey - Algoma granitoid complex
Levack gneiss complex
FL = Flett Twp
Faults
Grenville Front
N
0
50
kilometres

Figure 15.1. Location map showing the location of the study area, the distribution of Archean rocks in the south-central Canadian Shield in Ontario, and the distribution of rocks of the East Bull Lake intrusive suite. *Modified from* Easton (2000).

COUNTRY ROCKS

Gneiss Associations

Country rocks to the River Valley intrusion in Henry and Loughrin townships can be grouped into 3 gneiss associations; the characteristics of each are summarized in Table 15.1. From northeast to southwest, these are the Front, Street and Crerar gneiss associations (*see* Figure 15.2).

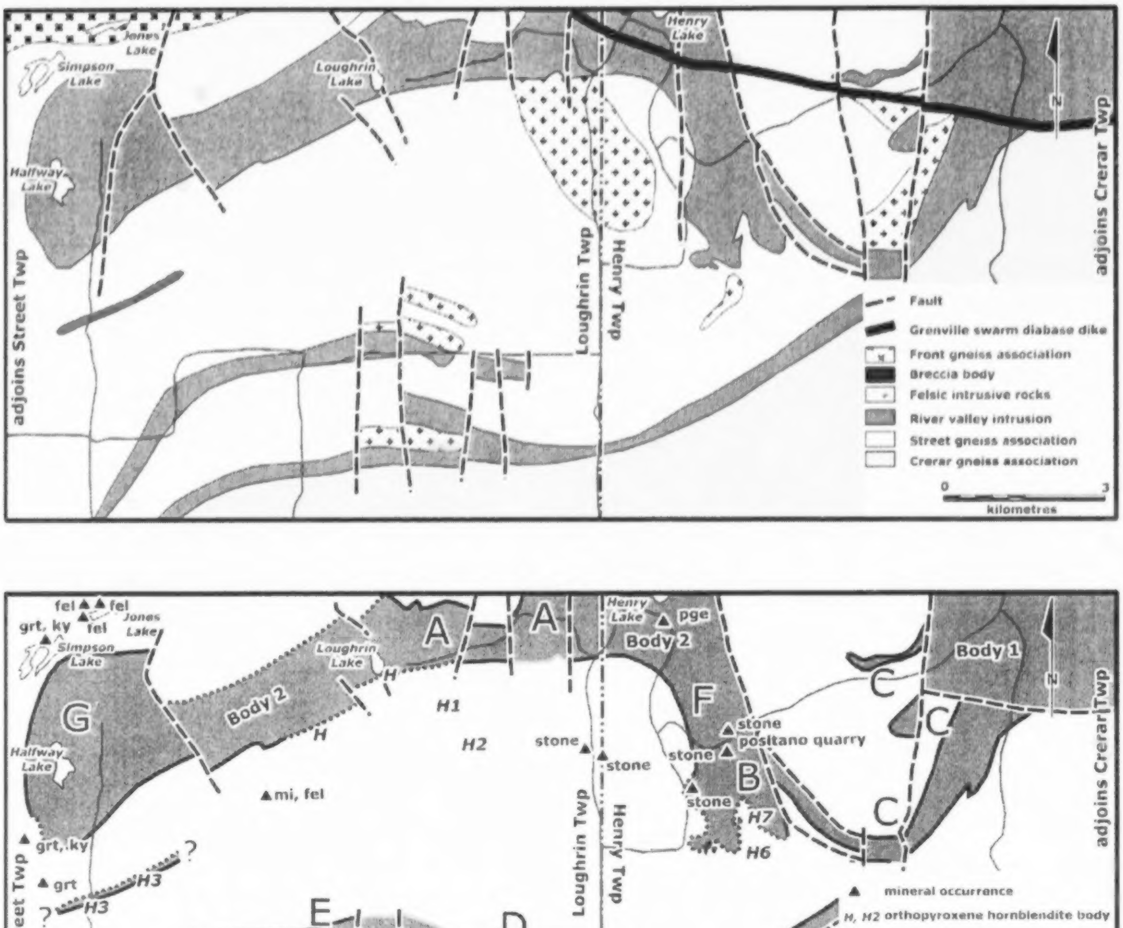
Jones Lake
Simpson Lake
Loughrin Lake
Halfway Lake
Henry Lake
N
adjoins Street Twp
adjoins Crerar Twp
Loughrin Twp
Henry Twp
Fault
Grenville swarm diabase dike
Front gneiss association
Breccia body
Felsic intrusive rocks
River valley intrusion
Street gneiss association
Crerar gneiss association
0
3
kilometres
fel
fel
grt, ky
fel
A
A
Body 2
pge
Body 1
G
Body 2
H
H1
H2
H
stone
stone
F
stone
positano quarry
stone
B
stone
H7
H6
C
C
C
mi, fel
grt, ky
?
H3
grt
?
H3
E
D
H5
H4
Body 3
H
H
Body 3
Body 3
grt
mineral occurrence
H, H2 orthopyroxene hornblendite body
B area noted in text
unknown contact/not exposed
fault contact
primary intrusive contact
younger intrusive contact
River Valley intrusion
0
3
kilometres

Figure 15.2. The upper figure is a simplified geological map of Henry and Loughrin townships. The lower figure shows the approximate distribution of rocks of the River Valley intrusion. Bold letters in the lower figure refer to specific localities discussed in the text.

Table 15.1. Comparison of rock units present within the 3 gneiss associations present in Henry and Loughrin townships. Rock types are listed from top to bottom in order of abundance, with most abundant first. Unit numbers in brackets under the Street gneiss association refer to map units in Street Township (Easton and Murphy 2000, 2002).

Front gneiss association	Street gneiss association	Crerar gneiss association
• granite gneiss, migmatitic (<10% granitic leucosome)	• migmatitic, quartzofeldspathic gneiss (unit 23, 22) are the main rock unit, may contain 5 to 25% garnet distributed throughout the rock in both melanosome and leucosome; includes diatextite and metatextite	• tonalite and granodiorite gneiss, minor granite gneiss of unknown age
• straight gneiss, consisting of rocks of mafic and felsic composition, commonly garnet bearing (5 to 15%)	• migmatitic mafic gneisses common (unit 4, 21) forming major map units, layers and pods	• megacrystic granodiorite intrusions and dikes
• mafic and diorite orthogneiss and amphibolite and felsite, locally fragmental, possibly derived from Huronian Supergroup metavolcanic rocks	• in northwest Loughrin Township, garnet ± aluminosilicate-bearing metasedimentary gneiss (unit 2, 3, 12?) is present	
• large granite pegmatite veins common and intrude a variety of rock units, most commonly mafic gneisses	• large granite pegmatite veins common and intrude a variey of rock units	• granite pegmatite veins not common, few are outcrop size
• older mafic dikes not common	• older mafic dikes not common	• 2 or 3 types of mafic dikes, typically boudinaged and folded with gneissosity
• Sudbury diabase dikes present locally, weakly metamorphosed	• Sudbury diabase dikes common, weakly metamorphosed	• Sudbury diabase dikes present locally, strongly metamorphosed
	• younger granite intrusions common	• younger granite intrusions generally not common

The Front gneiss association (*new term*) crops out only in northern Loughrin township, and is restricted to the area between the Grenville Front and the northernmost belt of River Valley intrusion rocks. Although there are some similarities between the Front gneiss association and rocks observed near the Grenville Front in adjacent Street Township to the east (Easton and Murphy 2002), there are some notable differences in Loughrin Township, including

1. the presence of Sudbury diabase dikes;
2. the presence of a zone of highly flattened "straight gneisses";
3. a greater abundance of granitic and diorite gneiss; and
4. fewer identifiable Huronian Supergroup metasedimentary rocks.

The Street gneiss association (*new term*) crops out throughout most of Loughrin township and is present in west-central Henry Township (*see* Figure 15.2). It consists of a variety of rock types previously described by the author in Street Township (Easton and Murphy 2002), as summarized in Table 15.1. Rocks of the Street gneiss association, however, generally contain more leucosome and have less discrete contacts (i.e., are diatextites rather than metatextites), especially the mafic gneissic rocks, than do the equivalent rock units in Street Township. Garnet is also less ubiquitous in Street gneiss association units than it is in Street Township.

The Crerar gneiss association crops out mainly in southern Henry Township (*see* Figure 15.2) and consists of a variety of intermediate composition orthogneiss previously described from adjacent Crerar Township to the east (Easton 2000; Easton and Hrominchuk 1999, 2001a).

The southernmost belt of River Valley intrusion rocks (*see* Figure 15.2) appears to mark the boundary between the Street and Crerar gneiss associations. It is not clear if this contact is tectonic, or whether it represents a lithologic break exploited by the River Valley intrusion during its emplacement.

Felsic Intrusive Rocks

Several large felsic intrusive bodies are present in central and northern Henry and Loughrin townships (*see* Figure 15.2). They consist mainly of gneissic granodiorite to monzogranite that is migmatitic to varying degrees. Felsic intrusions of this suite are most common within the Front and Street gneiss associations. Geochemically, these felsic gneisses resemble felsic intrusive rocks observed in Street Township (compare analyses 1 and 2, Table 15.2) that are Paleoproterozoic in age (circa 2460 Ma: Corfu and Easton 2000; Easton and Murphy 2002). It is equally possible, however, that some of these felsic intrusive rocks could be Mesoproterozoic in age, related to a mafic and felsic magmatic province active between 1270 and 1230 Ma in the northwestern Grenville Province (Easton and Ketchum 2002). Consequently, one of the larger intrusive bodies in west-central Loughrin Township was sampled for U/Pb geochronology. One of these felsic intrusions on the boundary road between Henry and Loughrin townships has been examined as a potential building stone (Sawitzky 1994).

It is not known if the few gneissic granite bodies observed within the Crerar gneiss association are similar in age to those found within the Street gneiss association. One granite body in southeast Henry Township contains inclusions of gabbroic rocks similar in appearance to the River Valley intrusion as well as quartzite, suggesting that it is Paleoproterozoic or younger in age.

Sudbury Diabase Dike Swarm

The Sudbury diabase dike swarm was emplaced into the Southern Province at 1238±4 Ma (Krogh et al. 1987), however, rocks of this swarm are present throughout the northwestern Grenville Province in Ontario (e.g., Ketchum and Davidson 2000; Easton 2002). Variably preserved segments of diabase dikes exposed throughout the map area are assigned on the basis of field appearance and geochemistry (*see* Table 15.2, analysis 3) to this dike swarm. The larger and better preserved dike segments are located within central Loughrin and western Henry townships within the Street gneiss association. The better preserved dikes appear little metamorphosed in the field and, in thin section, retain relict olivine grains and show only incipient development of metamorphic coronas around olivine, pyroxene and opaque mineral grains. In contrast, the more recrystallized dike segments, which are located mainly within the area underlain by the Crerar gneiss association, contain little relict primary mineralogy and show extensive metamorphic corona development. In addition to the country rock gneisses, Sudbury diabase dikes have been observed to cut felsic intrusive rocks, orthopyroxene hornblendite bodies, and rocks of the River Valley intrusion in the study area. A Sudbury diabase dike on the boundary road between Henry and Loughrin townships has been examined as a potential building stone (Sawitzky 1994).

Breccia Body

Although described by Lumbers (1971, 1973), this unusual breccia body located in northwest Henry Township has not been studied in detail prior to this study. It is hosted in recrystallized, foliated to gneissic, rocks of the River Valley intrusion. The body itself consists of angular fragments of apparently unmetamorphosed anorthosite and gabbroic anorthosite, metamorphosed gabbroic anorthosite, quartzite, and felsic intrusive rocks hosted in a grey-weathering, fine-grained matrix (Photo 15.1). Interestingly, it does not contain any fragments that can be clearly linked to the Front, Street or Crerar gneiss associations. In addition, mafic fragments of the River Valley intrusion are also rare to absent. In thin section, the matrix consists of an aggregate of fine-grained quartz, biotite, garnet, plagioclase and amphibole. Garnet is not xenocrystic, but rather is present as a symplectite of fine grains, similar to that observed in amphibolite of the Street gneiss association. This symplectite texture suggests that the matrix of the

Table 15.2. Representative chemical analyses of selected rock units from Henry and Loughrin townships. All chemical analyses were done at the Geoscience Laboratories, Geoservices Centre, Sudbury. Analysis #2 is *from* Easton and Murphy (2002). UTM co-ordinates are in Zone 17, NAD 83. Abbreviations: na = not analyzed, RVI = River Valley intrusion.

Analysis	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Sample No.	02RME-0018	96RME-0606	02RME-0014	02RME-0030	02RME-0097	02RME-0103	02RME-0106	02RME-0156	02RME-0070
Rock Type	granite gneiss	granite gneiss	Sudbury dike	breccia matrix	Grenville dike	RVI gabbro-norite	RVI leuco-gabbro gneiss	ortho-pyroxene hornblendite	potassium feldspar
Easting	544410	532060	544433	545031	549405	546218	546920	534909	534975
Northing	5160881	5162403	5160554	5163527	5162031	5159775	5160860	5157716	5163365
SiO_2 (wt %)	67.27	67.59	46.80	55.17	48.46	51.10	50.42	50.30	65.05
TiO_2	0.71	0.70	2.26	2.27	1.91	0.41	0.28	0.34	0.01
Al_2O_3	12.95	12.55	16.26	14.58	17.04	15.05	21.51	6.08	18.69
Fe_2O_3	7.37	2.18	3.84	12.79	3.97	0.77	1.83	2.21	0.03
FeO	na	4.20	10.47	na	9.69	6.50	4.40	9.03	na
MnO	0.13	0.10	0.21	0.16	0.19	0.16	0.11	0.21	<0.01
MgO	1.06	0.60	7.14	4.29	4.68	9.63	5.06	24.34	0.01
CaO	3.39	3.32	8.92	5.51	10.18	14.07	12.69	5.20	0.05
Na_2O	4.17	3.25	3.43	2.57	2.87	1.36	2.48	0.50	2.24
K_2O	2.92	3.60	0.84	2.22	0.33	0.38	0.32	0.08	14.20
P_2O_5	0.20	0.11	0.48	0.45	0.17	0.03	0.02	0.04	<0.01
CO_2	0.04	0.38	0.08	0.18	0.06	0.08	0.04	0.21	0.04
S	<0.01	<0.01	0.06	<0.01	0.01	0.04	0.02	<0.01	<0.01
LOI	0.30	0.86	<0.05	0.80	0.91	0.32	0.51	0.78	0.31
Total	100.47	99.06	100.65	100.81	100.40	99.78	99.62	99.11	100.59
Mg #	22.17	14.8	47.75	39.91	38.60	70.47	59.86	79.75	39.76
Zr/Y	7.4	6.6	5.6	7.8	3.9	2.6	2.6	3.6	3
Cr (ppm)	16	4	108	69	93	1271	123	3960	5
Ni	4	7	99	55	60	145	66	706	<2
Co	27	6	56	40	43	40	36	100	<12
Sc	15	10	30	27	36	48	32	29	<8
V	38	10	241	198	353	211	125	153	<4
Cu	<2	5	57	34	301	71	46	9	<2
Zn	96	42	124	126	98	52	44	84	10
Rb	77	90	10	65	6	9	<2	<2	745
Ba	789	970	505	618	<25	129	113	531	226
Sr	276	160	548	201	213	112	255	170	39
Nb	11	26	9	17	6	<2	<2	8	<2
Zr	243	440	167	297	120	29	21	148	3
Y	33	67	30	38	31	11	8	30	<1
Th	8	19	<4	<4	<4	<4	<4	<4	<4
U	<4	3.5	<4	<4	<4	<4	<4	<4	<4

breccia body was subjected to the same high-grade metamorphic event and retrogression effects as the country rocks in the map area; that is, the breccia body is older than 1000 Ma, the age of initiation of closure of U/Pb isotopic systems along the Grenville Front in this area (Corfu and Easton 2000). A chemical analysis of the matrix (*see* Table 15.2, analysis 4) indicates that it has the composition of a quartz diorite, and both major and trace element contents indicate that the rock is not alkalic. The contents of some elements, most notably TiO_2, P_2O_5, V, Ba, Nb, Zr and Y, are similar to those observed in Sudbury swarm diabase dikes (compare analyses 3 and 4, Table 15.2), and it is possible that this breccia may be related to the same magmatic event.

Grenville Swarm Diabase Dike

An unmetamorphosed diabase dike, present in northern Henry and Loughrin townships, that is associated with a prominent, linear, east-trending, aeromagnetic high is correlated with the Grenville diabase dike swarm that was emplaced at circa 590 Ma (Kamo, Krogh and Kumarapeli 1995). Significantly, this dike is offset along its length by north-trending faults, thereby providing a maximum age for these north-trending faults within the map area. A chemical analysis of this dike is given in Table 15.2 (analysis 5).

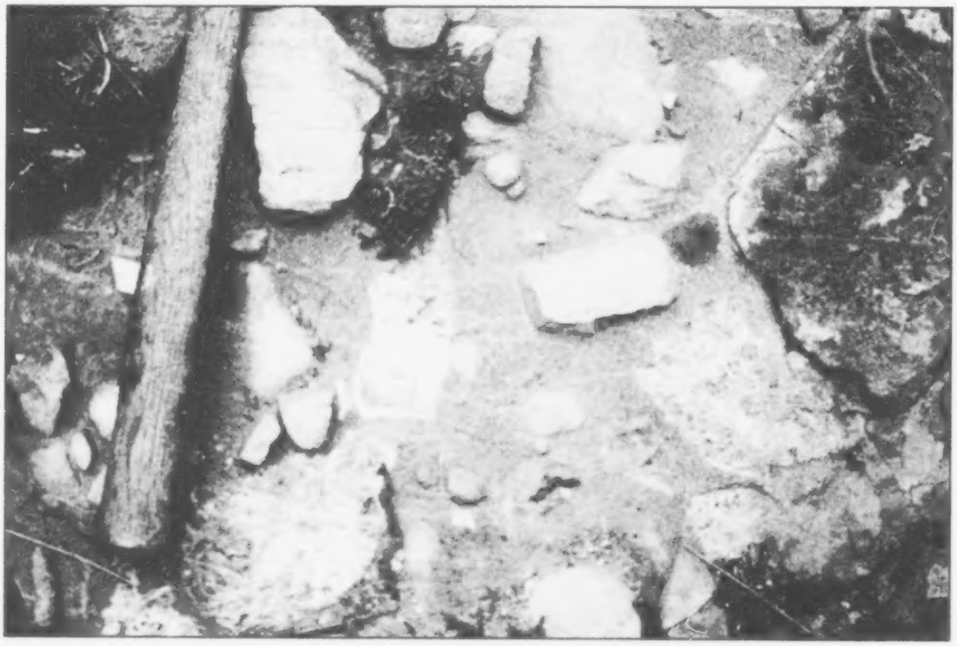

Photo 15.1. Diatreme-like breccia body located in northwest Henry Township (UTM Zone 17, 545031E 5163527N, NAD 83) containing angular fragments of unmetamorphosed and metamorphosed River Valley intrusion rocks, as well as quartzite and felsic intrusive rocks. Matrix of the body contains metamorphic garnet, indicating it is older than 1000 Ma. Hammer handle is 30 cm long.

RIVER VALLEY INTRUSION

The Paleoproterozoic East Bull Lake intrusive suite (James et al. 2002) extends from Elliot Lake in the west to River Valley in the east, and consists of several mafic layered intrusions emplaced between 2490 and 2468 Ma (Krogh et al. 1984; Corfu and Easton 2000; James et al. 2002) (*see* Figure 15.1). The largest of these intrusions are, from west to east, the East Bull Lake, the Agnew and the River Valley intrusions (*see* Figure 15.1). Previous maps of East Bull Lake intrusive rocks in Henry and Loughrin townships (e.g., Lumbers 1973) indicate that they are all connected directly to the River Valley intrusion. Consequently, for discussion purposes, these mafic intrusive rocks will be referred to as belonging to the River Valley intrusion, although as discussed elsewhere in this report, at least 3 separate intrusions may be present in Henry and Loughrin townships, only one of which may be directly connected to the River Valley intrusion.

Orthopyroxene Hornblendite Bodies

Bodies of orthopyroxene hornblendite, consisting of centimetre-size orthopyroxene phenocrysts in a fine-grained amphibole-plagioclase matrix, have been previously described by the author in Street Township (Easton 1998, 1999; Easton and Murphy 2002). Zircon from one of these bodies in Street Township has provided an age of 2468±5 Ma (Corfu and Easton 2002), which is similar in age to other intrusive rocks of the East Bull Lake intrusive suite (James et al. 2002). In Street Township, orthopyroxene hornblendite bodies are generally less than 100 m in size, and generally occur at the basal intrusive contact of intrusions correlated with the East Bull Lake intrusive suite.

Although orthopyroxene hornblendite bodies are common in Henry and Loughrin townships, several significant differences have been noted, as follows:

1. larger bodies, up to 400 m in size, occur in both Henry and Loughrin townships (designated by the letters H on Figure 15.2);
2. many bodies, including some of the largest ones, are not associated with the contact of the River Valley intrusion, for example, bodies H1, H2 and H4 on Figure 15.2 are located over 1 km from the contact; and
3. some bodies, such as body H3 on Figure 15.2, show a linear distribution and may represent boundinaged dikes.

The larger bodies contain the best preserved mineralogy, including relict olivine grains and golf-ball size, euhedral, orthopyroxene phenocrysts. In contrast, orthopyroxene grains in the smaller bodies are more extensively recrystallized, and generally exhibit rounded grain shapes and smaller grain sizes. Chemically, the bodies in Henry and Loughrin townships are similar to those found in Street Township (*see* Table 15.2, analysis 8).

Preliminary observations suggest that orthopyroxene hornblendite bodies are restricted to the Street gneiss association, although some bodies do occur in association with other River Valley intrusion rocks along the boundary between the Street and Crerar gneiss associations.

Rock Types

There are 2 main mafic intrusive rock types within the River Valley intrusion in the study area, namely, gabbronorite (based on both CIPW normative mineralogy and observed primary mineralogy, *see* Table 15.2, analysis 6) and leucogabbronorite (*see* Table 15.2, analysis 7). Locally, the leucogabbronorite can approach anorthosite in composition (>80% plagioclase). Over 65% of the exposed River Valley intrusion in Henry and Loughrin townships consists of leucogabbronorite. Texturally, gneissic varieties of these 2 main rock types predominate (Photo 15.2). Only in a few areas are primary mineralogy and textures partially preserved, the largest area of preserved rock being located in west-central Henry Township (*see* Figure 15.2, area B). In many outcrop areas, the gabbronorite and leucogabbronorite phases are interlayered on a centimetre to metre scale. In some of the larger outcrop ridges, gneissic varieties predominate on the flanks of the ridges, with foliated to undeformed, but partly to completely recrystallized varieties being preserved in the cores of the ridges. Easton and Hrominchuk (1999) and Hrominchuk (2000) noted a similar style of deformation and preservation in the River Valley intrusion in Dana and Crerar townships.

An important textural feature of the mafic and leucocratic gneisses of the River Valley intrusion in the study area is the general absence of layer-parallel or crosscutting leucosome phases (*see* Photo 15.2). In contrast, leucosome phases are abundant in the mafic gneisses present with the Street gneiss association (Photo 15.3). The presence of leucosome is an important field tool in distinguishing between the 2 types of mafic gneisses. In several parts of the map area, particularly in Loughrin Township, previous workers did not always successfully delineate the different mafic gneisses, in part because of their mapping scale, and, as a result, the older maps tend to exaggerate either the thickness or presence of belts of the River Valley intrusion. For example, a 500 m wide belt of mafic gneisses south of Loughrin Lake consists entirely of mafic gneisses of the Street gneiss association; and the thickness of the River Valley intrusion, along Third Concession Road in Loughrin Township (*see* Figure 15.2, area E), is no more than 500 m thick, not 1000 m thick as previously indicated (Lumbers 1973). There are some exceptions to the generalization that leucosome is rare within the River Valley intrusion, most notably, along the northern contact of body 2 (*see* Figure 15.2), however, these exceptions are restricted to areas of more intense deformation and metamorphism.

Garnet is a common visible accessory phase within the gneissic varieties of the River Valley intrusion, and appears to be more common than in similarly deformed rocks in western Crerar Township. This may result from higher metamorphic temperatures or pressures, or both, in Henry and Loughrin townships, or it may reflect subtle compositional differences between the 3 main bodies of River Valley rocks in the study area (*see* Figure 15.2).

Stratigraphy

Attempts to delineate a generalized stratigraphic column for River Valley intrusive rocks in Henry and Loughrin townships have not been completely successful, even in areas where primary features are partly preserved. This, in part, reflects the abundance of monotonous leucogabbronorite within the study area, as well as complications resulting from the highly deformed nature of the rocks, and the relationship between the 2 main generations of structural fabrics within the study area. Nonetheless, in a general sense, where a primary intrusive contact of the intrusion is present, the common sequence of rock units appears to be orthopyroxene hornblendite (as podlike bodies at the contact), gabbronorite (50 to 150 m thick), interlayered gabbronorite and leucogabbronorite (0 to 100 m thick), and leucogabbronorite (150 to 500 m thick). In detail, however, the observed stratigraphy at observed contacts varies considerably: in some areas, only leucogabbronorite is present, in others, only orthopyroxene hornblendite and gabbronorite are present; and in others, entire units are absent from the section.

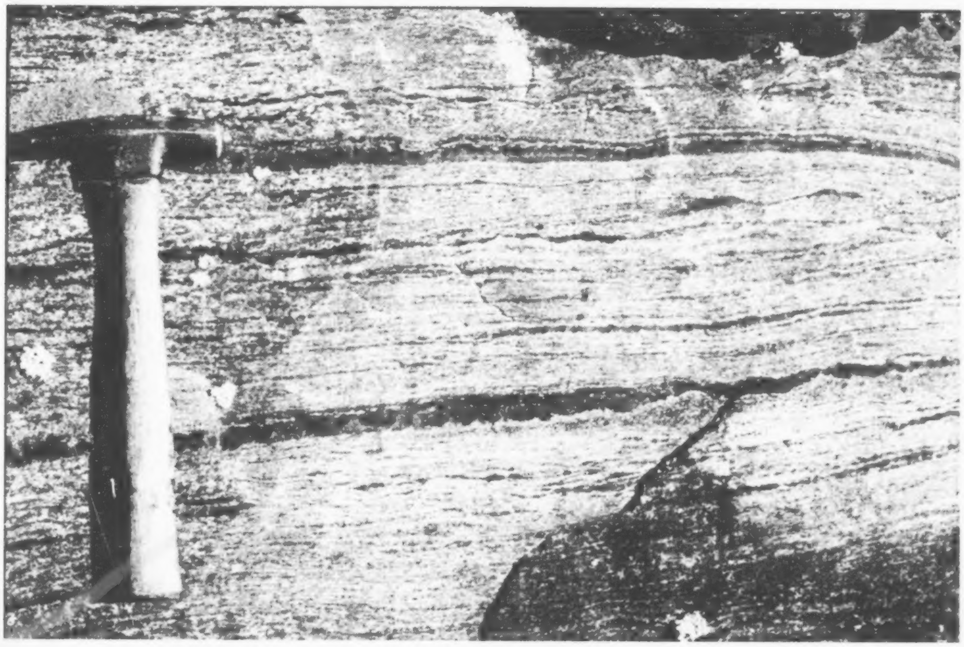

Photo 15.2. Typical leucogabbroic gneiss of the River Valley intrusion within Henry and Loughrin townships (UTM Zone 17, 548443E 5159789N, NAD 83). Note the lack of a prominent leucosome phase, either parallel to or discordant to gneissosity (compare with Photo 15.3). Hammer handle is 30 cm long.

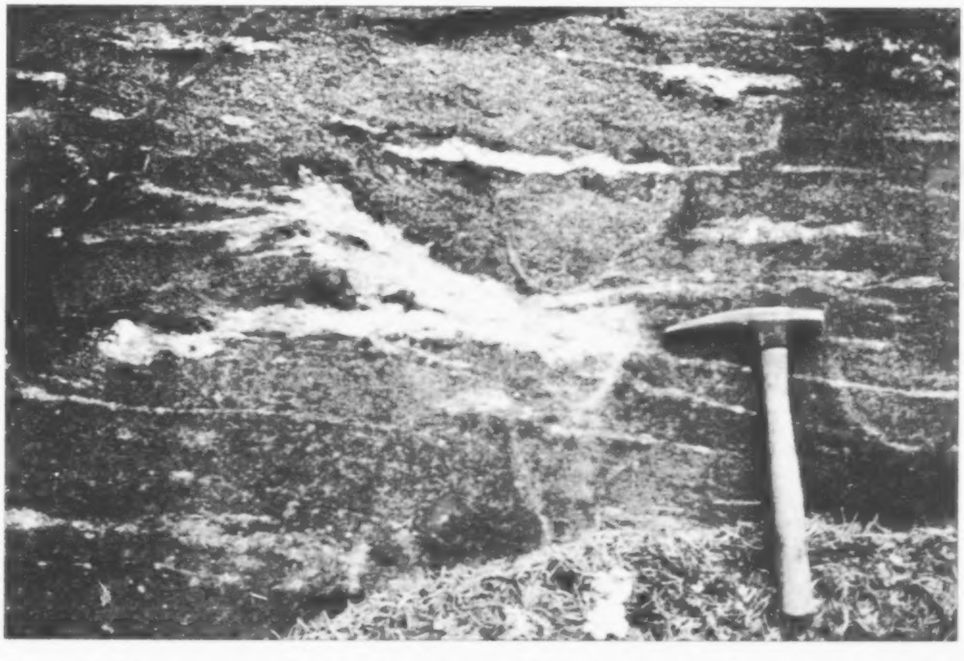

Photo 15.3. Typical mafic gneiss within the Street gneiss association (UTM Zone 17, 539522E 5157621, NAD 83). Note the prominent leucosome phases parallel to and discordant to gneissosity that serve to distinguish these older mafic gneisses from mafic rocks of the River Valley intrusion (compare with Photo 15.2). Hammer handle is 30 cm long.

Based on earlier maps which suggested that rocks of the River Valley intrusion had been folded (e.g., Lumbers 1973; Newman 1996), it had been hoped that it might be possible to observe the upper contact (roof) of the intrusion, especially as the roof has not been observed in other intrusions of the East Bull Lake intrusive suite (James et al. 2002). So far, this goal has not been realized. If the presence of orthopyroxene hornblendite bodies can be used to infer the basal contact of the intrusion, then it follows that the northern contacts of bodies 2 and 3 of the River Valley intrusion (*see* Figure 15.2) might represent upper contacts. The northern contact of body 2, however, appears to be a structural contact. In contrast, the northern contact of body 3 in the Third Concession Road area has been engulfed by gneissic granite, which has served to obliterate any upper contact. Consequently, the nature of the roof of the intrusion, and the rock types that may be present there, remain enigmatic.

Contacts

Several types of contacts have been observed for the River Valley intrusion, and include primary intrusive contacts, secondary intrusive contacts (where other rock units have intruded the River Valley intrusion), and fault contacts. The distribution of these contact types, where established, is shown on Figure 15.2. Of most importance to mineral exploration are primary intrusive contacts, since platinum group element-copper-nickel mineralization associated with the East Bull Lake intrusive suite is proximal to basal intrusive contacts (e.g., Hrominchuk 2000; James et al. 2002).

Regional Correlation and Implications for Mineral Potential

It was previously thought that the belts of mafic intrusive rocks located in the study area represented the westward continuation of the River Valley intrusion, be they possible feeders to the intrusion or infolded layers (Lumbers 1971, 1973; Newman 1996). Preliminary results of this study indicate, however, that only the mafic intrusive rocks located in northeast Henry Township (*see* Figure 15.2, body 1), that can be directly traced to rocks of the River Valley intrusion in Crerar Township, clearly represent the westerly extension of the River Valley intrusion. It is worth noting that the River Valley intrusion, both in Crerar and northeast Henry townships is hosted by country rocks of the Crerar gneiss association.

In contrast, mafic intrusive rocks in northern Loughrin and northwest Henry Township (*see* Figure 15.2, body 2) are hosted by rocks of the Street gneiss association, have associated orthopyroxene hornblendite bodies, and locally show preservation of primary textures and mineralogy, particularly in west central Henry Township. It is not clear if body 2 is a wholly separate intrusion, or if it is connected to body 1 by a thin septum of mafic rock, much like the east and west halves of the East Bull Lake intrusion are linked. Resolving this question has been difficult, in part because it is unclear if gneissic granite in area C of Figure 15.2 represents an area of country rock, or if the gneissic granite has simply intruded the mafic rocks in this area. A third, relatively thin (<500 m thick), intrusion (*see* Figure 15.2, body 3) may also be present in southern Henry and Loughrin townships along the boundary between the Street and Crerar gneiss associations.

Arguments in favour of bodies 2 and 3 being separate intrusions from the River Valley intrusion include the following observations, which take into account the increased metamorphic grade and deformation of the mafic intrusive rocks present in the study area:

1. the bodies are hosted by rocks of the Street gneiss association, believed to represent rocks preserved at a higher crustal level than the rocks represented by the Crerar gneiss association (Easton 2000);

2. the bodies are associated with orthopyroxene hornblendite bodies, which are notably absent from the River Valley intrusion in Dana and Crerar townships;
3. the fact that ultramafic and anorthosite layers are not common in bodies 2 and 3, even in the better preserved parts of body 2. Such layers are common in the River Valley intrusion in Crerar Township. In addition, the River Valley intrusion in Crerar Township has a distinct stratigraphy, whereas bodies 2 and 3 have no recognizable stratigraphic sequence.

If bodies 2 and 3 are separate intrusions from the River Valley intrusion, then it follows that they may have considerably different mineral potential. The fact that ultramafic layers and a distinct stratigraphy have not been identified in bodies 2 and 3 may indicate that these intrusions were less dynamic during their crystallization, which would indicate a less favourable environment for platinum group element enrichment according to Hrominchuk (2000). In addition, if they were separate and emplaced at a higher crustal level than the River Valley intrusion in Crerar Township, then bodies 2 and 3 may not have been subjected to the same factors, such as slow cooling, repeated magma injection, and the presence of a large volume and dynamic magma chamber that are thought to be important in generating the mineralization observed in the River Valley intrusion in Dana and Crerar townships (Hrominchuk 2000; James et al. 2002).

GEOPHYSICS

Integration of magnetic susceptibility measurements in the field, detailed mapping and the airborne geophysical data collected by WMC International Ltd. (Ontario Geological Survey 2002) has resulted in several observations concerning the geophysical characteristics of major rock units within the study area:

1. Mafic intrusive rocks of the River Valley intrusion (bodies 1 and 2) generally have low magnetic susceptibilities (<1.0) and appear as magnetic lows on maps of airborne magnetic data.
2. Mafic intrusive rocks of body 3 of the River Valley intrusion are associated with a linear magnetic high, but this high may be the result of neighbouring granitic gneiss, or a structural break associated with the boundary between the Street and Crerar gneiss associations.
3. Small, isolated, ovoid to round magnetic highs up to 500 m in diameter occur in parts of the River Valley intrusion, as noted by Newman (1996). The cause of these anomalies has not yet been determined, but they are not obviously associated with areas of less metamorphic recrystallization or unusual rock types or mineralogy.
4. Felsic intrusive rocks are characterized by moderate to high magnetic susceptibility (10 to 40) and appear as magnetic highs on maps of airborne magnetic data.
5. In general, the mapped contact of the River Valley intrusion occurs within 200 m or less of the boundaries between areas of magnetic lows (mafic intrusive rocks) and magnetic highs (country rock gneisses or felsic intrusive rocks).
6. The Grenville swarm diabase dike is characterized by high magnetic susceptibility (35 to 65), consistent with its expression as a linear magnetic high. The mapped width of the dike is about 50% smaller than the geophysical width of the dike.
7. The Sudbury swarm diabase dikes have low to moderate magnetic susceptibility (3 to 25), and are of insufficient size or magnetic contrast to be observed in the airborne magnetic data. Similarly, none of the orthopyroxene hornblendite bodies can be clearly observed in the airborne magnetic data. The breccia body appears as a small, ovoid of moderate magnetic intensity surrounded by rocks of more highly magnetic character.

MINERAL POTENTIAL

Platinum Group Element – Copper-Nickel Mineralization

Assay samples from this study were unavailable at press time, however, a considerable amount of assay data is currently available from the assessment files for parts of the study area, none of which is particularly encouraging. For example, data from 379 assay samples collected by Mustang Resources Corporation from area A (*see* Figure 15.2), had average values of 32 ppb combined Pt+Pd+Au, 52 ppm Cu and 30 ppm Ni (Wood 2002). Their highest assay sample contained 559 ppb Pt+Pd+Au, 346 ppm Cu and 865 ppm Ni (Wood 2002). The highest value reported by International Freegold Development Incorporated from part of the same area was from a sample containing 234 ppb combined Pt+Pd+Au, 954 ppm Cu, and 10 ppm Ni (Dimmell 2000).

The highest assay result from area D (*see* Figure 15.2) came from a malachite-stained rock adjacent a quart vein that analyzed 558 ppb Au and 3557 ppm Cu. The highest assay result from mafic gneiss in the same area, was 62 ppb Au, 93 ppb Pt, 80 ppb Pd, and 485 ppm Cu (Hanych 2002). Aquiline Resources Incorporated (2000) reported the presence of a sulphide-bearing horizon hosted within rocks of the River Valley intrusion north-northeast of Halfway Lake (*see* Figure 15.2, area G), but do not report any assay data from this horizon.

Within Henry Township, Hanych and Gore (2000) reported a sample containing 72 ppb Pt, 20 ppb Pd from the northernmost Positano quarry (*see* Figure 15.2, area F), with average Pt and Pd values of 11 ppb each. Their highest assay result, from a site located northwest of the Positano quarry, was 221 ppb Pt, 105 ppb Pd, and 440 to 850 ppm Cu. For comparison, in Dana and Crerar townships, Easton and Hrominchuk (2001a, 2001b) used a value of greater than 400 ppb combined Pt+Pd+Au as the cut-off for displaying platinum-group element occurrences in those 2 map sheets. So far, only the sample reported by Wood (2002) from northeast Loughrin Township would meet this criteria.

Although the basal contacts of both bodies 2 and 3 are exposed in several areas within the study area, nowhere has the author observed any inclusion-bearing phases that are commonly observed in association with the mineralized contact of the River Valley intrusion in Dana and Crerar townships (Hrominchuk 2000; Easton and Hrominchuk 1999). This, combined with the existing company assay data, the predominance of gneissic leucogabbronorite as the main rock unit, and the previously mentioned suggestion that bodies 2 and 3 of the River Valley intrusion may be separate intrusions from the River Valley intrusion exposed in Dana and Crerar townships, all suggest that rocks of the East Bull Lake intrusive suite in Henry and Loughrin townships may not be the best exploration targets for platinum group element-copper-nickel mineralization.

Building Stone

Several rock units in northwest Henry Township have been examined as possible building stones, notably leucogabbronorite gneiss (WIFCo and Dallaire 1985, Kirwan 1992) and gabbronorite of the River Valley intrusion (Positano 1995), Paleoproterozoic granite gneiss (Sawitzky 1994) and Sudbury diabase (Sawitzky 1994). All of these sites are characterized by minimal jointing, sufficient topography, and access to existing roads to make them viable prospects. Additional sites meeting this same characteristics are also present between areas B and F (*see* Figure 15.2), body 2 of the River Valley intrusion.

Feldspar

Several extraction pits were developed in large granite pegmatite bodies present in Loughrin Township prior to 1960 (Vos et al. 1981), the largest of these being present at Jones Lake in northwest Loughrin Township. A sample of feldspar was collected from this locality to test for possible rare metal potential (*see* Table 15.2, analysis 9). Lithium and cesium were both below detection limits in these samples, K/Ba ratios are less than 550, and Rb is 745 ppm. These elements, along with other key ratios, all indicate that the pegmatites in Loughrin Township fall in the Type 1b (barren) pegmatite type of Gordiyenko (1971) and, thus, have no rare-metal potential. It should be noted that these barren pegmatites are hosted in gneisses of either the Front of Street gneiss association. This does not preclude the possibility of rare metal pegmatites being hosted in the Crerar, Red Cedar Lake or Pardo gneisses located west of the study area, as suggested by Easton (2000).

Garnet and Kyanite

Locally, horizons ranging from 50 cm to 5 m thick containing between 15 to 30% garnet occur within the Street gneiss association, particularly in western Loughrin Township. Known occurrences in Loughrin Township include the MacDonald and Page occurrences, both described by Vos et al. (1981). The Page occurrence is considerably overgrown, and it is difficult to assess the potential of this occurrence, however, the host gneiss at this occurrence is not a particularly favourable host for significant garnet mineralization, based on the author's familiarity with known garnet occurrences in adjacent Street Township (Easton and Murphy 2002).

More promising are 2 garnet-kyanite occurrences located in western Loughrin Township. One occurrence, previously described by Easton and Murphy (2002) occurs as a large enclave of kyanite-garnet-biotite gneisses hosted in mafic gneiss of the River Valley intrusion near the Street Township boundary (UTM Zone 17, 533430E, 5158825N, NAD 83), and contains almandine garnet ranging in size from 15 to 50 mm and pale-blue kyanite laths up to 20 mm long. The second occurrence is located on the north shore of Simpson Lake (UTM Zone 17, 533975E, 5162471N, NAD 83), and is hosted in a package of metasedimentary gneisses similar to those that host the Ecosource garnet occurrences in Street Township (Easton and Murphy 2002), and likely represents the northeast continuation of this zone. Although the Simpson Lake occurrence contains golf- to tennis-ball-size garnets, the garnets are inclusion-rich and consist of aggregates of small garnet grains. Kyanite at the Simpson Lake occurrence, although locally abundant (up to 30% of the rock) is grey to dark grey in colour.

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16. Project Unit 00-101. Summary of Geophysical Projects and Activities

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INTRODUCTION

The following geophysical projects and activities were carried out in 2002 under the auspices of the Precambrian Geoscience Section:

1. Aeromagnetic levelling
2. Airborne data reformatting
3. Rock properties study
4. Timmins MEGATEM® survey
5. Other activities

Airborne geophysical surveys flown under the Operation Treasure Hunt initiative are described elsewhere in this volume (*see* Fyon et al.) and are not covered here.

Aeromagnetic Levelling

In order to enhance the quality of aeromagnetic datasets held by the Ontario Geological Survey (OGS) and reduce them to a common geomagnetic datum, a total of 35 surveys were reprocessed as part of the Operation Treasure Hunt initiative. The work, which was performed by Paterson Grant and Watson Ltd., comprised the microlevelling of individual surveying to remove flight line noise and the reduction of the data to a magnetic datum. The removal of residual flight line noise resulted in the reduction of "herring bone" effects in some surveys and an improvement in the appearance of imaged magnetic data, which can make it easier for users to observe small or subtle features that may have been previously obscured. The levelling of the surveys to a common magnetic datum allows OGS aeromagnetic datasets to be simply merged and assists clients by making it easier to insert their own data into the province-wide magnetic grid. Approximately 526 000 line kilometres of aeromagnetic data were reprocessed during the course of this project.

The microlevelling was performed by extracting the flight line noise from the gridded magnetic data using a combination of a high-pass and directional filters. The resulting grids were then used to subtract the flight line noise from the profile data. The process is described in more detail by Reford et al. (1990). The second part of this work comprised the reduction of the data to magnetic datum established by the Geological Survey of Canada (GSC) (Dods, Teskey and Hood 1985). This was achieved by first upward continuing the magnetic grid for each survey area to a constant elevation of 305 m in order to match that of the GSC master grid (datum). Difference grids were then created by subtracting the upward continued grids from the master grid. Through the application of a series of filters, the short wavelength features were removed from difference grid to yield smooth grids containing only very broad features with wavelengths in the order of 25 km or more. By subtracting values, obtained from the smoothed

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Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.16-1 to 16-4.

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difference grids, from the profile data, the survey areas were brought to a common magnetic datum. The process is described in further detail by Gupta et al. (1989).

The reprocessed data and derivative products (total field and second vertical derivative), along with the unreprocessed data will be released by the end of 2002. As part of this project, 6 "supergrids", combining the results from adjoining magnetic surveys, have been constructed in the following areas:

- Stormy–Sturgeon–Savant lakes
- Schreiber–Geco–Hemlo
- Wawa–Kapuskasing–Abitibi
- James Bay Lowlands
- Vickers–Pickle Lake
- Red Lake – Birch–Uchi lakes

Airborne Data Reformatting

In response to suggestions from clients, 33 airborne geophysical survey data sets are being reformatted under a contract with CGI-Stratagex. The surveys involved comprise approximately 482 000 line kilometres of airborne data acquired between 1975 and 1998. The geophysical data are being converted from older Centurion and proprietary database formats to more commonly used Geosoft® and universally accessible ASCII formats.

Physical Rock Properties Study in the Matheson and Kirkland Lake Areas

As part of the Ontario Treasure Hunt initiative, a collaborative physical rock properties study was undertaken between the Ontario Geological Survey and McMaster University. The contribution from McMaster University has been completed with methods and preliminary results discussed in Deschamps (2000, 2001) and Deschamps and Morris (2001). Measurements of magnetic susceptibility and remanence, density and seismic properties were undertaken for 474 specimens, collected within areas covered by the Matheson and Kirkland Lake airborne geophysical surveys. The Ontario Geological Survey contribution will consist of hand specimen and thin section descriptions of a representative selection of the samples. A brief summary report of the results will be completed by the end of March, 2003. We are integrating magnetic susceptibility data collected by bedrock mapping field crews and are assessing the feasibility of conducting ongoing rock properties data collection as part of each bedrock mapping project. These data will be incorporated into a database and will result in more effective interpretation and modelling of the results of airborne geophysical surveys through the use of comparative ground-controlled measurements.

Timmins MEGATEM® Survey

A 11 133 line kilometre MEGATEM® II survey was flown, by Fugro Airborne Surveys Inc., north of Timmins in February and March of 2002. The MEGATEM® II system comprises powerful time-domain EM equipment and a towed-bird magnetometer mounted on a Dash 7 aircraft. The EM transmitter is distinguished by its large dipole moment, which is significantly more powerful than the earlier MEGATEM® and GEOTEM® systems. It is thought that the greater depth of penetration of this survey will provide explorationists with a superior tool to explore an area that has the potential to host economic base and precious metal deposits and is overlain by thick, conductive overburden. The survey was jointly funded by FedNor (Industry Canada), Falconbridge Limited, the OGS, and the GSC, which also supervised the project as part of the Discover Abitibi! initiative.

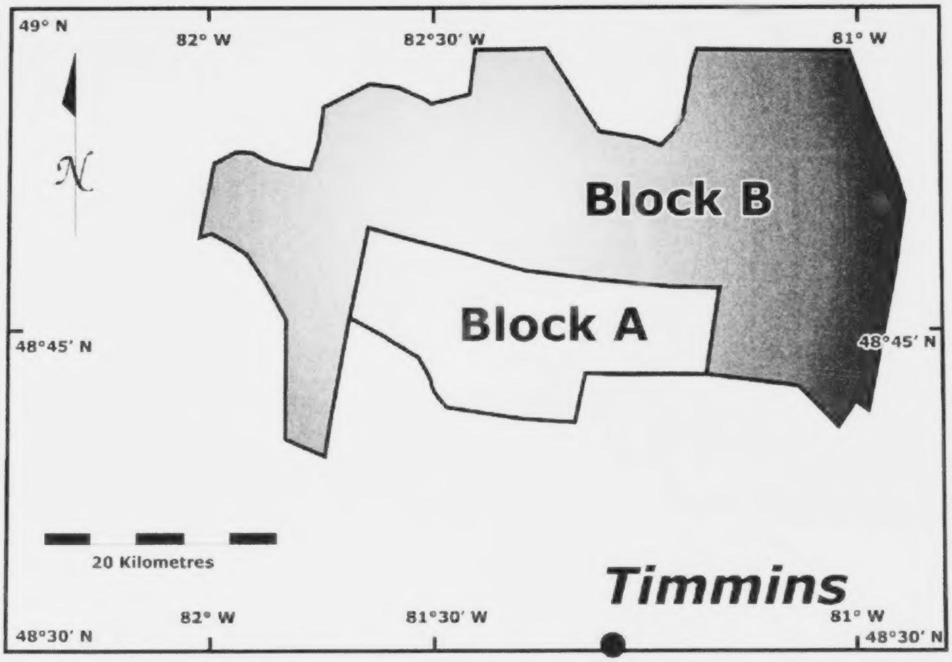

Figure 16.1 Limit of the Timmins MEGATEM® survey area.

Block A (Figure 16.1) was flown with a 125 m flight-line interval and a transmitter frequency of 30 Hz. Block B was flown using a 150 m line spacing and a 90 Hz transmitter frequency. These specifications were chosen to best meet the needs of the parties involved. The results of the survey will be made public in a joint GSC–OGS release in 2002.

Other Activities

Geophysical support was provided to geoscientists in the Precambrian Geoscience Section of the OGS in order to assist with ongoing Precambrian bedrock mapping projects. The integration of geophysics into the mapping effort is considered to be a priority as many of the project areas are now covered by high-quality airborne survey data that have been acquired in recent years.

Client support, arising from enquiries by the public, has been provided as required and has included airborne survey design and planning for a First Nations Community. The Geophysical Atlas, available on the web (http://www.mndm.gov.on.ca/MNDM/MINES/OGS/gpxatlas/index.html), continues to provide information, to the geoscience community, on the availability of geophysical data from the OGS.

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17. Sudbury Targeted Geoscience Initiative (TGI) (2000–2003): Overview and Update

D.E. Ames

Geological Survey of Canada, Natural Resources Canada, Ottawa

INTRODUCTION

The Sudbury Targeted Geoscience Initiative (TGI) is in the final year of a three-year program (2000 to 2003) designed to improve geoscience knowledge of the geologic setting and processes involved in creating and modifying the world-renowned nickel-copper-platinum group element (PGE) deposits of the Sudbury Igneous Complex (SIC) (1850 Ma), Sudbury Structure (Ames et al. 2001). Canada's PGE mineralization in Sudbury is the second most important in the world after Noril'sk, Russia (Farrow 2001). Historically, exploration focus in Sudbury was concentrated on massive sulphide discoveries, however, many new opportunities exist for copper-PGE deposits in the new century. An increased knowledge base of the ore-forming and ore-modifying processes will lead to new exploration opportunities in this historical mining camp.

PROJECT OVERVIEW

This project involves integrated structural, magmatic–hydrothermal and sulphide mineralogical and geochemical studies to determine the controls on the distribution and formation of Sudbury ore deposits. Multiple geological processes were involved in generating and modifying the deposits with emphasis in this project on the structural (before, during and after the formation of the SIC at 1850 Ma) and hydrothermal–magmatic controls.

Four main subprojects include:

- Volatile-alteration study of the Sudbury Igneous Complex: detailed regional traverses (D.E. Ames, A.G. Galley, I.M. Kjarsgaard)
- North Range structure: Sudbury Breccia and sulphide veins in footwall rocks of the Sudbury Igneous Complex, Levack Embayment; 1:10 000 scale mapping (D. Legault, B. LaFrance)
- South Range structure: structural analysis of the western Sudbury Basin; 1:50 000 scale mapping (A.J. Dubois, K. Benn)
- Trace element and trace mineral study of nickel-copper-platinum group element (PGE) ores, Sudbury (D.E. Ames, C.E.G. Farrow, I.M. Kjarsgaard, E. Pattison, I.R. Jonasson, R.A. Zierenberg, D.H. Watkinson)

Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.17-1 to 17-10.

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Field work for the 3 mapping-based subprojects of the Sudbury TGI was completed in 2002 (Figure 17.1). A 1:10 000 scale map of the Levack Embayment is scheduled for publication in the winter of 2003 at the Geological Survey of Canada. In addition, a series of Geological Survey of Canada Current Research papers will be presented in the winter 2003 issue. An up-to-date multiparameter GIS database of the Sudbury Structure comprising new and compiled geoscience data will provide a new regional context and important reference material for industry, academia and government. A bedrock geology map compilation is linked with geophysical, geochronological, mineralogical and ore grade data. New geochemical data include major elements, trace elements and isotopic data from Archean and Proterozoic footwall rocks, including pseudotachylite, and, from 12 transects through the SIC, more than 60 nickel-copper ± PGE, copper-PGE, zinc-lead-copper ore deposits and also the Onaping, Vermilion and Onwatin formations.

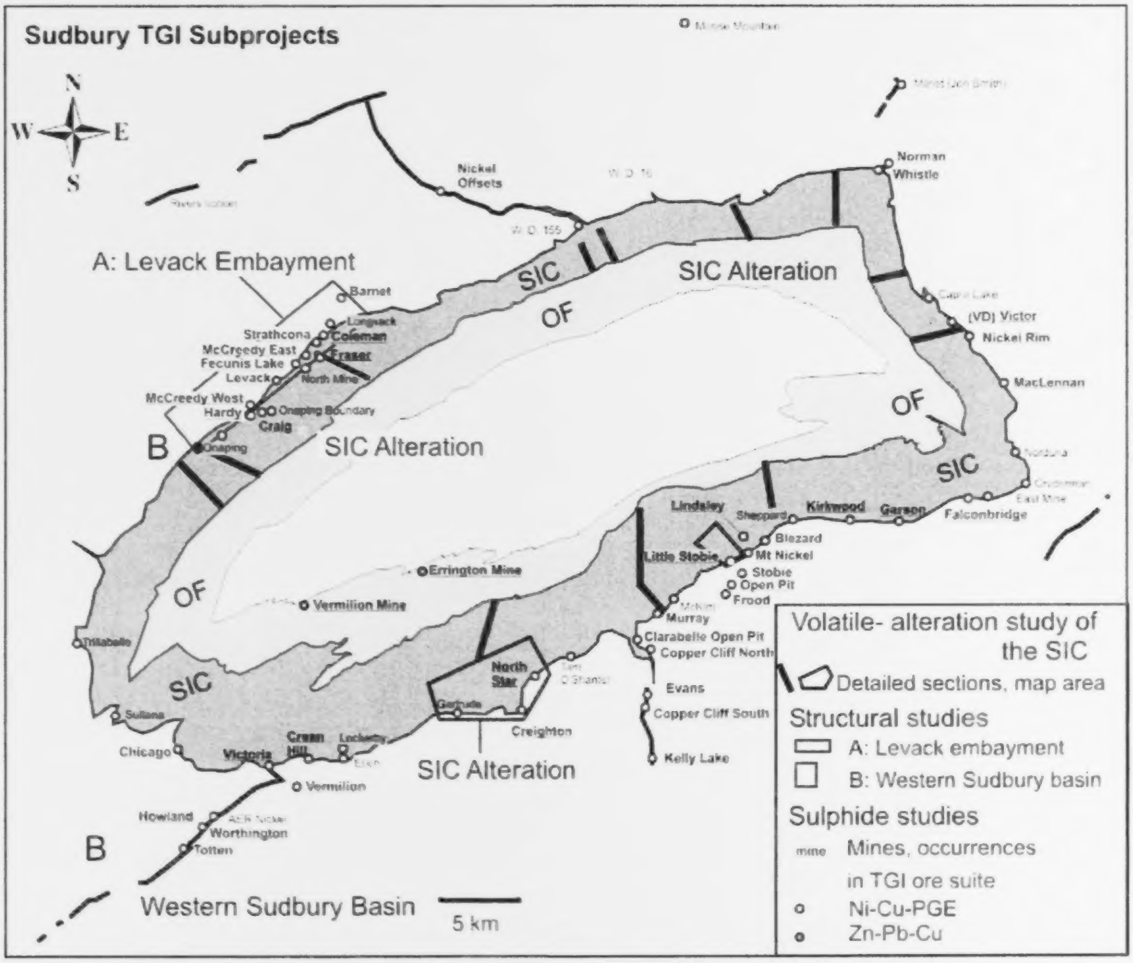

Sudbury TGI Subprojects
N
W
E
S
Moose Mountain
Nickel Offsets
W.D. 16
W.D. 155
Norman
Whistle
A: Levack Embayment
Barnet
Longvack
Coleman
Strathcona
McCreedy East
Fraser
Fecunis Lake
Levack
North Mine
McCreedy West
Hardy
Onaping Boundary
Craig
B
Onaping
SIC
OF
SIC Alteration
Capre Lake
(VD) Victor
Nickel Rim
MacLennan
OF
SIC
East Mine
Falconbridge
Lindsley
Sheppard
Kirkwood
Garson
Blezard
Little Stobie
Mt Nickel
Stobie
Open Pit
Frood
McKim
Murray
Clarabelle Open Pit
Copper Cliff North
Errington Mine
Vermilion Mine
OF
SIC Alteration
Trillabelle
SIC
Sultana
Chicago
Victoria
Crean Hill
Lockerby
Ellen
North Star
Gertrude
Tam O'Shanter
Creighton
Evans
Copper Cliff South
Kelly Lake
SIC Alteration
Vermilion
Howland
AER Nickel
Worthington
Totten
B
Western Sudbury Basin
5 km
Volatile- alteration study of the SIC
Detailed sections, map area
Structural studies
A: Levack embayment
B: Western Sudbury basin
Sulphide studies
mine Mines, occurrences in TGI ore suite
Ni-Cu-PGE
Zn-Pb-Cu

Figure 17.1. Location map of the 4 TGI subprojects in the Sudbury Structure. Abbreviations: SIC, Sudbury Igneous Complex; OF, Onaping Formation.

SUBPROJECTS

1. Volatile-Alteration Study of the Sudbury Igneous Complex

CREIGHTON–GERTRUDE–NORTH STAR STUDY

(D.E. Ames, I.M. Kjarsgaard, E. Pattison)

Detailed mapping and sampling (~250 samples) of the norite phase of the SIC above the Creighton–Gertrude–North Star nickel-copper-PGE deposits was completed to determine the distribution of halogens and alteration assemblages within an ore-bearing embayment structure. The 2002 field study in the Creighton super-embayment focussed on diamond-drill holes that intersected the Creighton and Gertrude deposits. Field ultraviolet fluorescence observations indicated that the distribution of the chlorine-rich scapolite alteration (Ames et al. 2001) is greatest proximal to ore (Figure 17.2). These field data are being followed up with petrography, semi-quantitative X-ray diffraction and mineral chemistry to characterize the alteration types of the SIC and determine their paragenesis according to magmatic, hydrothermal or metamorphic origins.

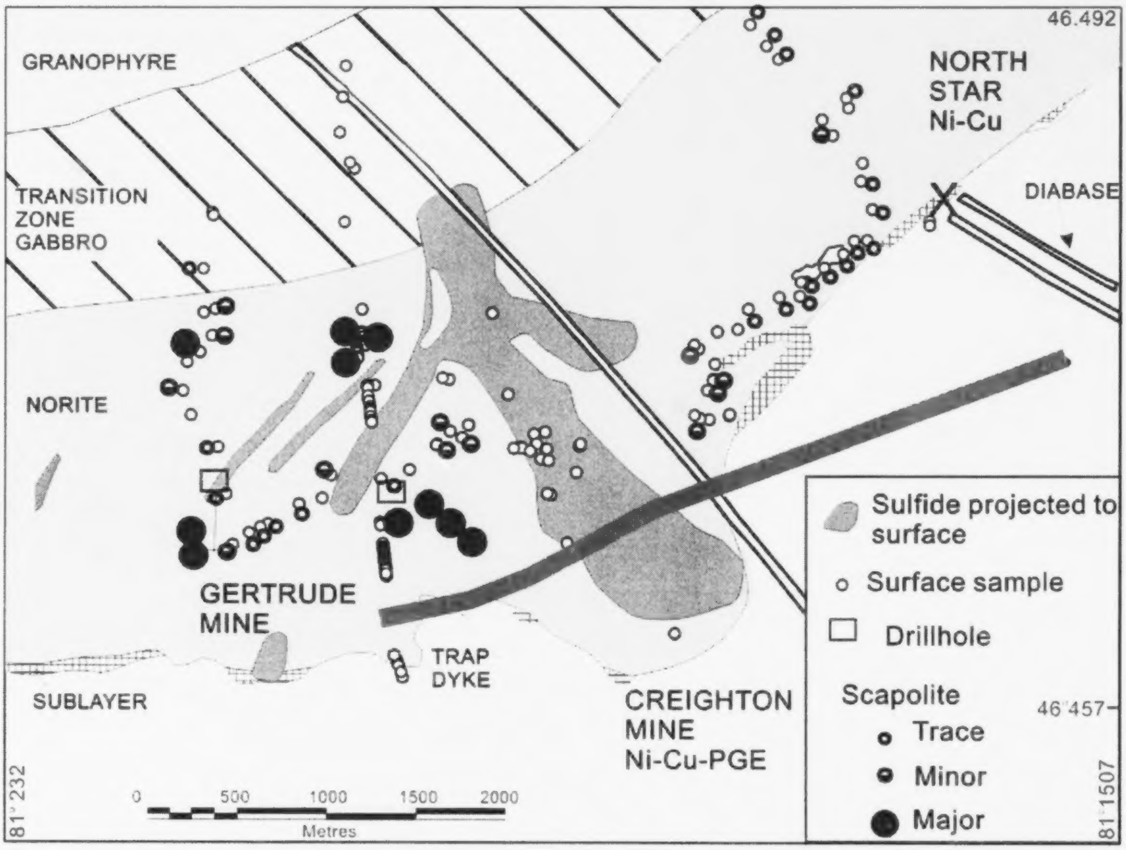

46.492
GRANOPHYRE
NORTH STAR Ni-Cu
TRANSITION ZONE GABBRO
DIABASE
NORITE
Sulfide projected to surface
○ Surface sample
☐ Drillhole
Scapolite
Trace
Minor
● Major
GERTRUDE MINE
TRAP DYKE
SUBLAYER
CREIGHTON MINE Ni-Cu-PGE
46°457
81°232
81°1507
0
500
1000
1500
2000
Metres

Figure 17.2. Preliminary map of the distribution of chlorine-rich scapolite in the Creighton–Gertrude–North Star mine area, Creighton super-embayment, South Range, Sudbury Structure. Projected orebodies *from* Farrow and Lightfoot (2002).

GRANOPHYRE STUDY

(A.G. Galley, D.E. Ames, I.M. Kjarsgaard)

The purpose of the study of the granophyre phase of the SIC is to record the evolution of volatiles during the crystallization history of the body. The importance of volatile activity has been linked by several authors (Farrow and Watkinson 1992, 1997; Molnar, Watkinson and Jones 2001) to the formation of PGE-rich sulphide mineralization within the footwall to the SIC. Although there is a large (>1000 m) interval between the PGE-rich environment and the main granophyre phase, the volatiles may have been focussed during the crystallization history along syncrystallization structures that may connect the lower and upper parts of the intrusive complex. Recognition of these structures through volatile concentration may be used as a "smoking gun" to more effectively direct deep exploration for the small, PGE-enriched sulphide vein systems.

The field component of the study involved 12 traverses across the SIC, which included sections through the North, East and South Ranges, respectively (*see* Figure 17.1). The purpose of the traverses were to complete detailed geological sections along which variations in granophyre texture, grain size, and composition were recorded. Vein, dike and fracture orientations were recorded, along with the presence of miarolitic cavities. Where cavities were recognized, their size distribution and density were recorded, along with the compositions of the minerals that fill the cavities. This process was quantified by taking a series of measurements at each outcrop within a 25 by 25 cm square. Where possible this process was carried out on vertical and horizontal surfaces with the aim of cataloguing the three-dimensional distribution of the cavities.

Field and analytical investigations to date have resulted in evidence supporting the hypothesis (Cowan, Riller and Schwerdtner 1999) that the granophyre cooled separately from the norite and transitional phases of the SIC. In most of the sections examined, evidence for volatile exsolution and associated super cooling of the granophyre phase is restricted to near the centre of the granophyre (Figure 17.3). Textural and mineral chemical evidence includes the presence of acicular amphibole and coarse-grained, pegmatitic amphibole growth, miarolitic cavity concentrations and high fluorine-apatite (F = 2.35 weight %, Cl = 0.15 weight %) in the middle of the granophyre. The presence of fine-grained, more equigranular textures on both the upper and lower contacts of the granophyre phase, less altered to fresh granophyre through petrographic observations, plus the presence of aligned plagioclase crystal formation are further evidence of cooling and crystallization from both the top and bottom of the granophyre. Orientations of linear zones of both intense granophyre growth and miarolitic cavities (Figure 17.4) range from parallel through to perpendicular to igneous contacts, suggesting a variation in stress controls during formation. The original, relatively anhydrous, granitoid melt concentrated a volatile phase that exsolved during late-stage super cooling and rapid crystallization.

It has become apparent, through the co-ordination of the various TGI studies in the granophyre, alteration of the SIC and footwall studies that a thorough investigation of the volatile history of the granophyre phase should include examination of the felsic bodies within the transitional quartz gabbro and norite phases of the SIC (*see* Figure 17.3). From the subsequent investigation of these felsic bodies, it is now clear that, in addition to the granitoid xenoliths described by Marsh and Zieg (1999), there are also coarse-grained felsic pegmatite and finer grained granophyre dikes and sills (*see* Figure 17.4). The felsic pegmatites have diffuse margins, and are associated with more quartz-rich gabbro at both the base and top of the mafic part of the SIC, but are more abundant as both dikes and sills within the transition zone quartz gabbros. The pegmatite bodies are crossed by sharp-sided, equigranular to sparsely plagioclase-phyric felsic dikes that, particularly in the South Range, form a series of sills directly below the main granophyre phase. The felsic pegmatoids are typical features within a cooling mafic intrusion where the solidification front periodically fractures, resulting in low-pressure zones in which remaining fluids can congregate (Marsh 1995). The presence of both sills and dikes (*see* Figure 17.4) of this material in the quartz gabbro of the transition zone may be indicative that this zone represents the top of one magma chamber, with the granophyre phase having been emplaced in its final position separately. The sharp-sided nature of the felsic dikes and lack of textural variation with the host gabbros suggests that the felsic part of the SIC was emplaced after much of the gabbro and quartz gabbro phases were crystallized. The evidence for a multi-phase history to the granophyre supports observations first made by Peredery and Naldrett (1975). The possibility that the granophyre had a separate cooling history from the remainder of the SIC has implications as to whether there can be a direct linkage between the volatile histories of the 3 SIC phases and their involvement in ore-forming or ore-modification processes in the footwall rocks.

Detailed sections through the 12 traverses through the granophyre from field, mineral chemical and isotopic data allow characterization of the composition, crystallization history and role of the volatile phases within the SIC. Data will be released through a GSC Current Research paper in the winter 2003, a journal paper and all data compiled in the Sudbury TGI GIS database. Collaboration with researchers examining the relationship between footwall granophyre and PGE mineralization in the Footwall, Sublayer and Offset environments ensures that these will be used to present a more comprehensive assessment of the timing and role of the SIC granophyre in the metallogenic evolution of the Sudbury region.

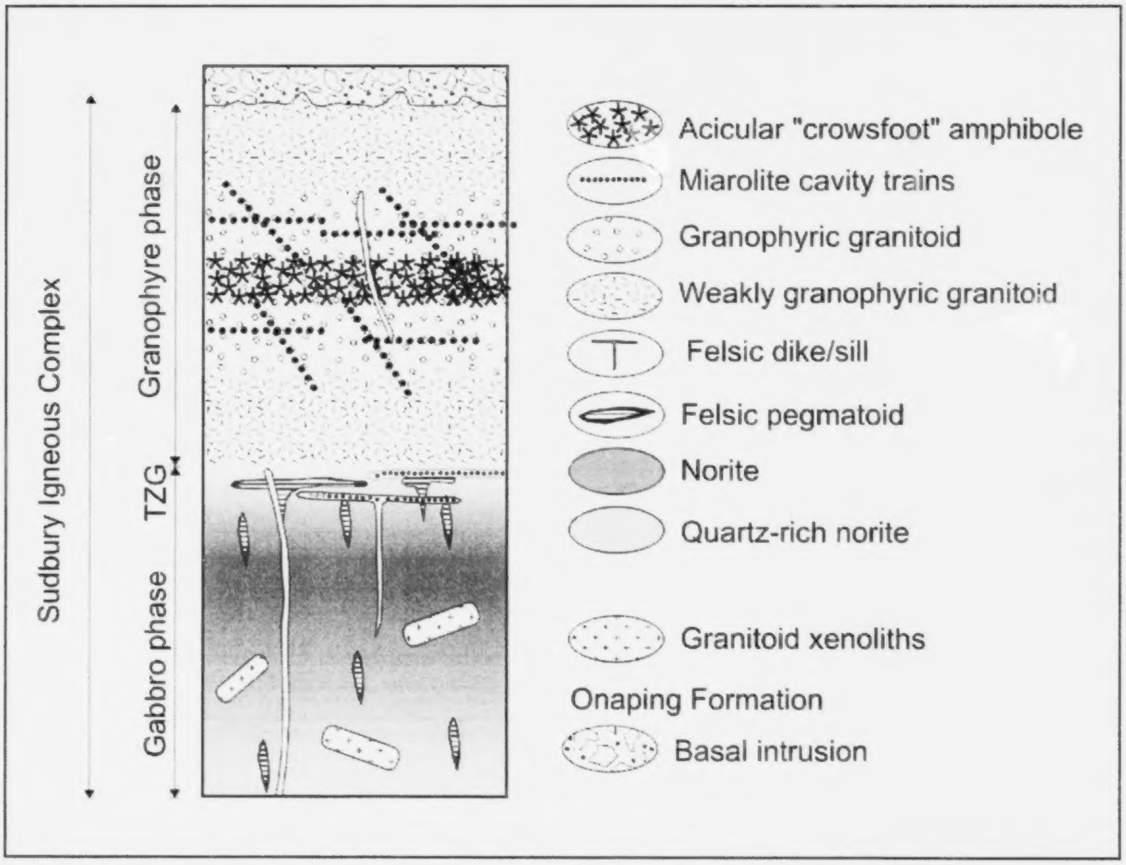
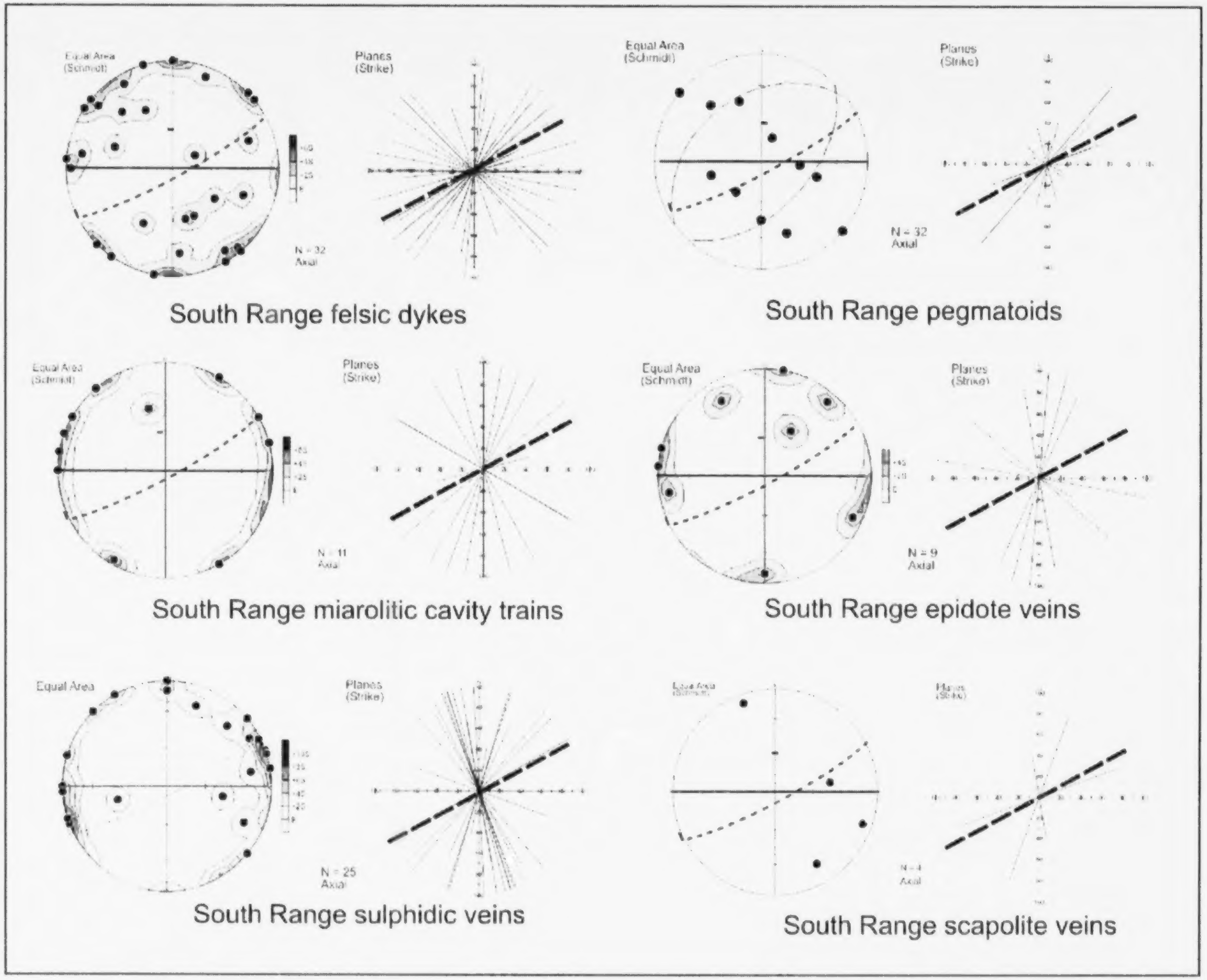

Sudbury Igneous Complex
Granophyre phase
TZG
Gabbro phase
Acicular "crowsfoot" amphibole
Miarolite cavity trains
Granophyric granitoid
Weakly granophyric granitoid
Felsic dike/sill
Felsic pegmatoid
Norite
Quartz-rich norite
Granitoid xenoliths
Onaping Formation
Basal intrusion

Figure 17.3. Generalized stratigraphic section of the Sudbury Igneous Complex emphasizing textural and felsic dike components. Abbreviation: TZG, transition zone gabbro.



South Range felsic dykes

South Range pegmatoids

South Range miarolitic cavity trains

South Range epidote veins

South Range sulphidic veins

South Range scapolite veins

Figure 17.4. Orientation of felsic dikes, miarolitic cavity trains, pegmatoid patches, epidote veins, sulphide veins, and scapolite veins in the Sudbury Igneous Complex, South Range. Bold dashed line represents the orientation of the SIC and footwall contact.

2. North Range Structure: Sudbury Breccia and Sulphide Veins in Footwall Rocks of the Sudbury Igneous Complex, Levack Embayment

(D. Legault, B. LaFrance, D.E. Ames)

Magmatic copper veins in footwall copper-PGE deposits of the North Range of the SIC occur in conjugate and concentric fractures cutting across concentric zones of the Sudbury Breccia. The Sudbury Breccia originated by fracturing and friction melting of the basement rocks during the expansion of shock waves generated during the initial contact–compression stage of the Sudbury impact. Spray (1997) suggested that further brecciation occurred during reactivation of the breccia zones as normal superfaults during collapse of the crater rim, or as upthrust faults, if the Sudbury Basin represents the collapsed central uplift of a larger eroded crater. The concentric and conjugate fractures formed later than the Sudbury Breccia, either during the excavation or modification stages of the impact, and they provided pathways for the migration and emplacement of the copper-rich melts. Determining the kinematics, orientation, and spatial distribution of the Sudbury Breccia and fractures is therefore essential for understanding the emplacement and geometry of the footwall copper-PGE deposits.

The main objectives of the MSc study by D. Legault at Laurentian University are

1. determine the geometry, composition and spatial distribution of the Sudbury Breccia in the Levack Embayment of the North Range

2. Define pre-, syn- and post-Sudbury Breccia structures in the footwall Levack Gneiss

3. determine the geometry and relative timing of copper-PGE sulphide mineral emplacement with respect to brittle deformation of footwall rocks, epidote-chlorite ± actinolite and potassic-quartz alteration veins

The second and final year of mapping was completed in the Levack Embayment (*see* Figure 17.1) at 1:10 000 scale and, in more detail, at the Barnet copper-PGE showing involving plane tabling, sulphide veins of the Levack adit and a wide zone of Sudbury Breccia southeast of the Barnett area. The association of volatiles, such as the halogens fluorine, chlorine and bromine, with the footwall copper-PGE veins within Sudbury Breccia has been reported (Farrow and Watkinson 1992, 1997, 1999; Jago, Morrison and Little 1994; Molnar, Watkinson and Jones 2001; Hanley 2001). A study of the halogen content of new and known Sudbury Breccia zones in the Levack Embayment is in progress.

The 1:10 000 map of the Levack Embayment will be published as a Geological Survey of Canada Open File product in the winter of 2003, and field results will be published by D. Legault, B. LaFrance and D.E. Ames in the 2003 release of Geological Survey of Canada Current Research.

3. South Range Structure: Structural Analysis of the Western Sudbury Basin

(A.J. Dubois, K. Benn)

As part of the Sudbury TGI, this study was initiated in 2001 (Dubois and Benn 2001) and involves extensive mapping in the southwestern part of the SIC and its footwall (Trill, Drury, Fairbanks and Denison townships) (*see* Figure 17.1). This two-year project, supported under an Ontario Geological Survey–University of Ottawa Collaborative Project Agreement is summarized elsewhere in this volume (Dubois and Benn, this volume). It emphasizes the identification, description and classification of structures related to deformation events before, during and after the formation of the SIC. The project also aims to propose possible models for the deformational history of the southwestern part of the Sudbury Basin after 1850 million years ago.

The area was selected for mapping and structural analysis because it has undergone a large degree of deformation in the past 1850 million years that has strongly modified the SIC. This makes the study area particularly interesting for an analysis of the deformational history because unravelling the complex geological structure may lead to the development of new mineral exploration targets. An expectation of the project is the ability to identify which structures accommodated the post-impact shortening of the western part of the SIC leading to apparent thrust imbrication.

During 2 summers of field work, in 2001 and 2002, over 457 outcrops were mapped and extensive sampling was carried out for petrographic studies. Bedrock mapping and preliminary petrographic results resulted in the recognition of 3 structurally distinct zones within the study area. The most highly deformed zone, the South Range shear zone (SRSZ; Shanks and Schwerdtner 1991), appears to be bounded by the Cameron Creek and Cameron Lake faults on its northern side and by the Creighton fault on its southern side. To the north and the south of the SRSZ, the SIC is unstrained or only weakly strained, and the structures in the footwall rocks most likely record tectonic events before deformation in the South Range shear zone (and possibly pre-impact).

Structures, south of the SRSZ and in the Onaping Formation, suggest a bulk pure shear with a vertical maximum principal stretching direction. This structural framework suggests that post-Sudbury event ductile deformation, in the study area, may have occurred in a transpressive regime, with simple shear partitioned into (mainly) dextral-reverse shear zones that may bound rock volumes wherein bulk pure shear was accommodated by a system of anastomosing shear zones.

Detailed studies have been undertaken on 8245 km of diamond-drill core belonging to INCO, Falconbridge Limited and FNX Mining Company. The data from diamond-drill logs and re-logging of the core will be used to establish structural profiles in key parts of the study area. In 2002 to 2003, the data collected from bedrock mapping, the diamond-drill hole logs and available geophysical data will be used to constrain the geometries of the rocks and structures in the subsurface, so that a three-dimensional model of the study area may be constructed. Structural modelling software (Noddy$^{\text{TM}}$) will then be used to test possible kinematic models to explain deformation in the western Sudbury Basin after the formation of the SIC.

The results of the mapping, petrographic studies, diamond-drill core logging and structural modelling should provide a new framework for targeting potential mineral exploration targets, and also for proposing models for the formation, and subsequent deformation of the Sudbury impact structure and its hosted mineral deposits. In particular, structural imbrication of the footwall rocks with parts of the SIC may prove to be of particular interest for mineral exploration programs. A preliminary report of this work will be published as an Open File Report by the Ontario Geological Survey in 2002. This will be followed by the publication of a bedrock geology map, final Open File Report and three-dimensional model by the Ontario Geological Survey in 2003.

4. Trace Element and Trace Mineral Study of Nickel-Copper-Platinum Group Element Ores, Sudbury

(D.E. Ames, C.E.G. Farrow, I.M. Kjarsgaard, E. Pattison, I.R. Jonasson, R.A. Zierenberg, D.H. Watkinson)

The aim of the sulphide study of the Sudbury Structure deposits and host rocks (*see* Figure 17.1) is to determine the trace element characteristics of the ores in diverse deposit environments; to identify trace element trends and associations related to mineralogy; to identify the contributions of elements from magmatic and crustal sources; and to identify the source(s) of sulphur to elucidate the complex processes involved in Sudbury ore generation. The Sudbury TGI ore and host rock collection includes well-located ore samples from past-producing mines; producing mines; new discoveries and subeconomic deposits from a variety of sources, including the GSC National Research Collection of Minerals and Ores (samples collected since 1887); universities; mining companies; the Ontario Geological Survey; and original field work (*see* Ames et al. 2001, Table 25. 1). The Sudbury TGI ore and host rock collection contains over 500 samples with extensive geochemistry completed comprising whole rock, rare earth elements and trace elements including F, Cl, Se, Bi, Te, Hg, As, Sb, Pt, Pd, Au and Ag. Sulphur isotopic data are complete for 260 Sudbury samples including massive ore, disseminated ore, mineral separates and Archean and Proterozoic country rocks and from transects across the Archean Levack gneiss, ore zones, SIC and through the Onaping Formation into the basinal sediments of the Onwatin Formation.

The mineralogy, paragenetic sequences and mineral chemistry on the nickel-copper-PGE sulphide samples is near completion and will be merged through a GIS database with the sulphide geochemistry, map location and photographs of polished ore slabs.The sulphide study complements the extensive sampling of the host rocks to the orebodies in the SIC and footwall subprojects of the Sudbury TGI. Database compilation incorporates the new Sudbury TGI information with mineralogical and deposit data from the literature, industry, academia and other government sources.

CONCLUSIONS

These detailed studies target geoscience problems related to the controls on and modification of Canada's world-class nickel-copper-PGE ore deposits and generate new geoscience information to be made available as digital map and database products. This project will provide a lithologic, alteration and structural framework for the mineral exploration industry and other clients with rapid transfer of knowledge to the Canadian public. Improved deposit models should increase the effectiveness of exploration for deposits nationally and internationally, thereby, increasing the competitiveness of Canadian mining companies.

ACKNOWLEDGMENTS

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18. Project Unit 01-005. Structural Analysis of the Southwestern Sudbury Basin: Implications for Mineral Exploration

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INTRODUCTION

The Sudbury Targeted Geoscience Initiative (TGI) is a three-year program (2000 to 2003) designed to gain a better understanding of 1) the geological setting of the world's largest nickel-copper-platinum group element (PGE) deposits, associated with the Sudbury Igneous Complex (SIC); and 2) the processes involved in ore deposit genesis and subsequent deformation. The Sudbury TGI is a collaborative project that involves the Geological Survey of Canada, the Ontario Geological Survey, mining industry partners and several universities, including the University of Ottawa.

As part of the Sudbury TGI, this study was initiated in 2001 (Dubois and Benn 2001) and is an investigation of the lithologic and, especially, structural controls on nickel-copper-PGE mineralization in the SIC and its immediate footwall. This two-year project, supported under an Ontario Geological Survey – University of Ottawa Collaborative Project Agreement, involves extensive mapping in the southwestern part of the SIC (Trill, Fairbanks, Drury and Dension townships) and its footwall. It emphasizes the identification, description and classification of structures related to deformation events, which occurred before, during and after the formation of the SIC. The project also aims to propose possible models for the post-Sudbury event deformational history of the southwestern part of the Sudbury Basin.

The area was selected for mapping and structural analysis because it has undergone a large degree of deformation after 1850 Ma that has strongly modified the Sudbury impact structure. This makes the study area particularly interesting for an analysis of the deformational history because unraveling the complex geological structure may lead to the development of new mineral exploration targets.

At the end of the project, we should be able to determine which structures accommodated the post-impact shortening of the western part of the SIC leading to apparent thrust imbrication. Products of this project will include structural profiles and three-dimensional models to show the geometries of rock units and structures in the subsurface; to quantify the degree of shortening in order to better understand the original shape of the basin; and finally to propose a model for the structural evolution and the kinematic history of this part of the Sudbury Structure. These objectives will be attained by using the data collected during mapping and petrographic study, by incorporating geological and geophysical data made available by the mining industry and by application of a sophisticated software package for modelling tectonic deformations.

REGIONAL GEOLOGIC SETTING

The geology of the Sudbury Basin is shown in Figure 18.1a and the geology of the study area is presented in Figure 18.1b.

Summary of Field Work and Other Activities 2002.
Ontario Geological Survey, Open File Report 6100, p.18-1 to 18-12.

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The Sudbury Structure is located on the boundary of the Superior Province to the north, and the Southern Province to the south and east (*see* Figure 18.1a). All bedrock in the area is Precambrian in age. Rocks from the Superior Province consist of Archean gneiss, metasedimentary and metavolcanic rocks. Rocks from the Southern Province consist of metavolcanic and metasedimentary rocks of the early Proterozoic Huronian Supergroup (2500 to 2219 Ma; Card, Innes and Debicki 1977; Corfu and Andrews 1986).

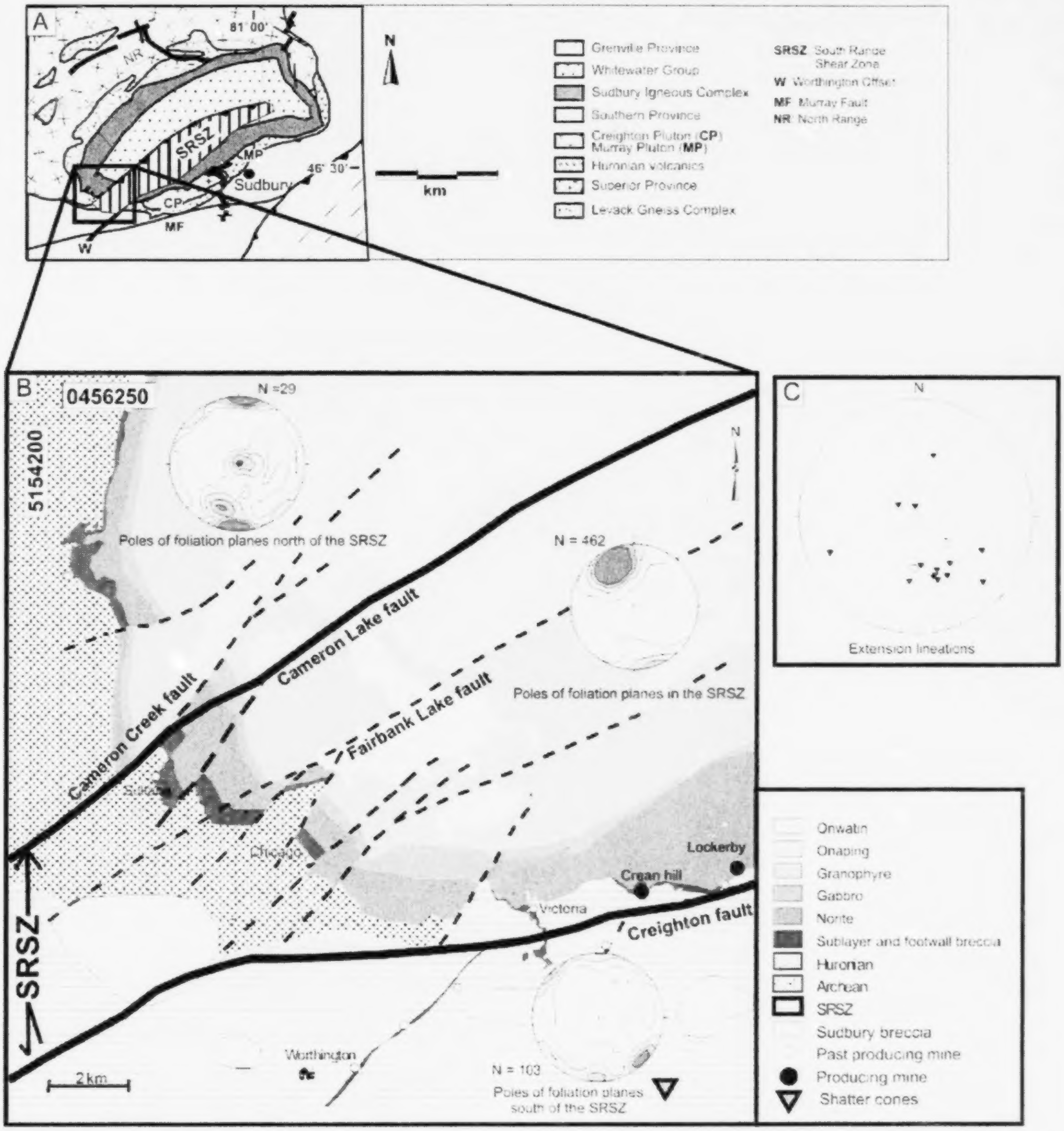

A
81 00'
NR
SRSZ
MP
Sudbury
46 30'
CP
MF
W
N
km
Grenvile Province
Whitewater Group
Sudbury Igneous Complex
Southern Province
Creighton Pluton (CP)
Murray Pluton (MP)
Huronian volcanics
Superior Province
Levack Gneiss Complex
SRSZ South Range Shear Zone
W Worthington Offset
MF Murray Fault
NR North Range
B
0456250
5154200
N =29
Poles of foliation planes north of the SRSZ
N
N = 462
Cameron Lake fault
Cameron Creek fault
Fairbank Lake fault
Poles of foliation planes in the SRSZ
Chicago
Lockerby
Crean hill
Victoria
Creighton fault
SRSZ
Worthington
N = 103
Poles of foliation planes south of the SRSZ
2km
C
N
Extension lineations
Onwatin
Onaping
Granophyre
Gabbro
Norite
Sublayer and footwall breccia
Huronian
Archean
SRSZ
Sudbury breccia
Past producing mine
Producing mine
Shatter cones

Figure 18.1. a) Geological map of the Sudbury Basin and location of the study area. The South Range shear zone (SRSZ) is drawn *from* Shanks and Schwerdtner (1991b). **b)** Geology of the study area. Equal area projections represent the poles of foliation planes in 3 distinct areas: north of the SRSZ, within the SRSZ, and south of the SRSZ. **c)** Extension lineations within the SRSZ. Triangles refer to a reverse sense of movement interpeted in the field; circles to a normal sense of movement interpeted in the field.

The Murray fault zone, which is a major structural feature in the southern part of the Sudbury Basin, is thought to have originated as an extensional fault during Huronian sedimentation (Card and Hutchinson 1972). Huronian Supergroup metasedimentary rocks were intruded by plutons composed of granite (2388 +20/–13 Ma: Krogh, Davis and Corfu 1984) and anorthositic gabbro (2480 +10/–5 Ma: Krogh, Davis and Corfu 1984). The metasedimentary and metavolcanic rocks of the Huronian Supergroup were folded prior to the intrusion of the Nipissing diabase sills (2219 Ma: Card 1978, Bennett, Dressler and Robertson 1991).

The Penokean Orogeny (1890 to 1830 Ma: Van Schmus 1980; Hoffman 1989) resulted in deformation of the rocks in the Sudbury area. Regional shortening associated with the Penokean Orogeny resulted in large-scale folding and displacements along south-dipping thrust faults (Zolnai, Price and Helmstaedt 1984). The Penokean Orogeny deformed the Huronian Supergroup and reactivated the Murray fault zone as a south-dipping thrust fault (Cooke 1946).

The "Sudbury event" is believed to have been a meteorite impact (Dietz 1964) that resulted in the formation of the Sudbury breccias and of a large melt body that subsequently crystallized to form the Sudbury Igneous Complex (SIC). The impact event occurred 1850 million years ago (Krogh, McNutt and Davis 1982). The SIC, which occupies a large part of the Sudbury Basin, is a tripartite magmatic assemblage, consisting of i) norite overlying the Footwall Breccia at the base of the SIC, ii) gabbro and iii) granophyre. The initial shape of the SIC may have been that of a flat-lying tabular impact melt sheet (Grieve, Stoffler and Deutsch 1991). Alternatively, the SIC may have originally had an inverted funnel shape (Shanks and Schwerdtner 1991b; Cowan, Riller and Schwerdtner 1999).

A magmatic event consisting of granitic plutonism (1750 Ma: Davidson and van Breemen 1994) occurred in the south of the Sudbury Basin (Fueten and Redmond 1997). Subsequently, at approximately 1450 million years ago, the Sudbury Basin underwent another orogenic event (Fueten and Redmond 1997). This period of deformation led to the formation of the South Range shear zone (SRSZ) (Fueten and Redmond 1997). Ductile thrusting on the SRSZ was interpreted by Shanks and Schwerdtner (1991a) to be responsible for the present subelliptical shape of the SIC. Much of the study area lies within the SRSZ, as defined by Shanks and Schwerdtner (1991a). This period of deformation was followed by the emplacement of the Sudbury olivine diabase dike swarms at 1235 Ma (Fahrig and Wanless 1963; Van Schmus 1965).

The last orogenic phase that affected the Sudbury Basin was the Grenville Orogeny (1070 to 1000 Ma) (Zolnai, Price and Helmstaedt 1984; Davidson 1992), which strongly reworked rocks to the southeast (*see* Figure18.1b). Within the Sudbury Basin, the Grenvillian orogenic event is characterized by dominantly brittle deformation. This deformation event also reactivated the east-northeast-striking Murray fault zone, resulting in right-lateral displacements (Card 1968).

The western part of the present study area (*see* Figure 18.1b) consists of Neoarchean (>2600 Ma) granitic plutons, gneissic, metavolcanic and metasedimentary units of the Superior Province. In the southern part of the study area, the Neoarchean rocks are unconformably overlain by metasedimentary rocks of the Huronian Supergroup, which is part of the Southern Province. The Huronian Supergroup rocks consist of clastic sedimentary rocks of the McKim and Matinenda formations and volcanic rocks of the Elsie Mountain and Stobie formations. Huronian Supergroup strata dip steeply to the south-southwest.

The composition of the SIC varies from the North Range to the South Range in the Sudbury Basin. In the study area, located in the South Range (*see* Figure 18.1b), norite consisting of cumulates of plagioclase, hypersthene and interstitial augite, quartz and ilmenite is 2000 m thick compared to a 600 m thickness in the North Range (Naldrett and Hewins 1984). The quartz gabbro, also called transition zone, is 600 m thick and 3 times the thickness of the North Range quartz gabbro (Naldrett and Hewins 1984). The quartz gabbro consists of a dark gray and coarse-grained mineral assemblage of plagioclase, quartz, biotite, primary amphibole and augite. The granophyre in the study area is extremely sheared and is about 1600 m thick, which is 200 m thicker than in the North Range (Naldrett and Hewins 1984). The granophyre consists mainly of biotite and micrographic and granophyric intergrowths of quartz and plagioclase.

MINING ACTIVITIES IN THE STUDY AREA

The study area includes active and past-producing mines (*see* Figure 18.1b) that are located on the Worthington Offset dike (Victoria Mine, Kidd Copper Mine, Totten Mine and Worthington Mine); and at the contact between the SIC and the footwall (Chicago Mine, Sultana Mine, Crean Hill Mine (INCO) and the Lockerby Mine (Falconbridge Limited)). Thousands of tons of ore were extracted from the Victoria Mine and 3500 tons of nickel and copper were extracted, between 1891 and 1897, from the Chicago Mine (Card 1965). At present, only the Crean Hill and Lockerby mines are active. Several companies and prospectors have active mining claims in the study area, including INCO, Falconbridge Limited, FNX Mining Company Inc., Wallbridge Mining Company Limited, Aurora Platinum Corporation, Consolidated Venturex Holdings Limited and Pierre Maillet. Mining companies have conducted diamond drilling in the area for at least 60 years; in particular, Falconbridge Limited has diamond-drill logs for approximately 60 km of core. Ground and airborne geophysical surveys have been conducted by private companies and also by government agencies over many years.

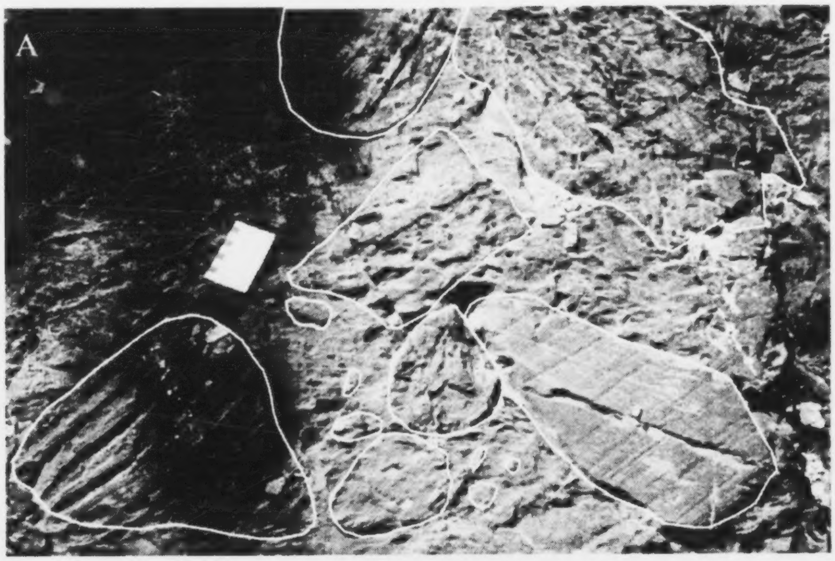
STRUCTURAL GEOLOGY

Impact-Related Structures

Shatter cones are distributed in a 20 km diameter ring around the SIC (Gibson and Spray 1998). They are present in the southeast corner of the study area (*see* Figure 18.1b). Shatter cones are shock-induced structures generated by a large impact (Dietz 1968). The cone aperture is defined by striations in the rocks. Our measurements of the different aperture angles of cones gives a mean value of 46.62° (±11.76°). Sagy, Reches and Fineberg (2002) studied the process of shatter cones formation and found a linear correlation between the mean striation angle of shatter cones and the distance between the centre of the impact and the shatter cone formation site. According to their formula, shatter cones in the southeast of the study area (*see* Figure 18.1b) were formed at a distance of roughly 35 km (±5 km) from the centre of the impact.

Sudbury Breccia is also present in the studied area (*see* Figure 18.1b). It consists of clasts of Huronian Supergroup rocks hosted within a dark fine-grained matrix. The colour of the breccia matrix may be lighter where the breccia occurs in arkosic rocks (Elliott Lake Group). Most outcrops in the study area allow observations to be made only on a horizontal surface. Clasts range, in a horizontal plane, from centimetres to decametres in size (Figure 18.2a) and do not display a preferred orientation. On 1 outcrop, observations on a vertical plane reveal that the breccia clasts are strongly elongated and plunge steeply to the north (Figure 18.2b). The clast shapes indicate that the strain state of the breccia is constrictional. The outcrops of Sudbury Breccia are interpreted to be part of the western extension of the South Range breccia belt (SRBB).

The SRBB is interpreted to be the eroded remains of a slump fault that facilitated terrace formation inside the crater by block rotation along normal fault planes (Spray 1997). Spray (1997) estimated that the amount of displacement on the SRBB is about 2.5 km. However, bedding planes within units of the Huronian Supergroup to the north and the south of the SRBB have similar orientations with steep southward dips suggesting that rigid rotations of fault blocks did not accompany the proposed normal fault displacement on the SRBB in the study area.



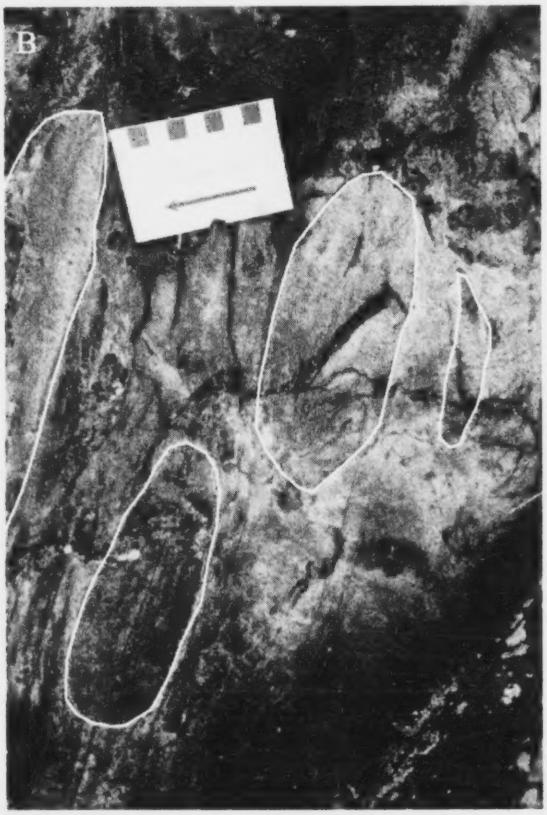


Figure 18.2. a) Clasts from Huronian Supergroup rocks in Sudbury Breccia observed on an horizontal surface, and **b)** on a vertical surface, looking east.

Post-Impact Ductile Structures

Much of our work has focussed on post-impact deformation, which, in the study area, is expressed mainly within the SRSZ. Field mapping and petrographic studies are complemented by detailed study of diamond-drill core made available by INCO, Falconbridge Ltd. and FNX Mining. The detailed studies of diamond-drill core has provided important information on the rock units and structures present in the subsurface, to about 1500 m depth. It also allowed us to determine the orientation of the base of the SIC in the study area. The contact between the SIC and footwall rocks is steeply north dipping in the southern part of the study area and steeply east dipping in the western part of the study area.

In the Sudbury Basin, the SRSZ is at least 80 km long and up to 10 km wide(*see* Figure 18.1a). The SRSZ is bounded to the north by folded rocks of the Whitewater Group, which includes the Onaping, Onwatin and Chelmsford formations; and to the south by unstrained rocks of the SIC (Shanks and Schwerdtner 1991a). To the east of the study area, the SRSZ may have accommodated a net thrust displacement of approximately 8 km (Shanks and Schwerdtner 1991a).

In the study area, strong shearing related to the SRSZ has affected parts of the Onaping Formation, the southern part of the SIC and the footwall of the SIC. The SRSZ is bounded to the north by the Cameron Lake and Cameron Creek faults and it is limited by the Creighton fault to the south (*see* Figure 18.1b). The SRSZ is characterized by penetratively foliated and lineated rocks (Figures 18.3a and 18.3b). It affects every lithology from the Onaping Formation in the northeast to the Huronian Supergroup rocks in the southwest. The ductile deformation is strongly developed and many quartz veins are folded and transposed into the foliation plane. The deformation within the SRSZ overprinted pre-existing structures.

The SRSZ is so strongly expressed that it overprints all pre-existing deformation. On average, the foliation planes measured in the SRSZ strike 060° and dip 60° to the south (*see* Figure 18.1b). Some deformed quartz veins indicate a dextral sense of shear on foliation planes, when viewed on horizontal surfaces. Sense of shear was inferred from field observations of porphyroclast deformation associated with the extension lineation measured on foliation planes. Twenty-two outcrops showed a reverse sense of displacement indicating a south-over-north sense of shear (Figure 18.4a) and 2 outcrops revealed a normal sense of displacement. The 2 outcrops displaying a normal sense of shear are in the Onaping Formation and in the footwall (*see* Figure 18.1c). Petrographic study confirms that the dextral-reverse sense of shear is predominant in the SRSZ.

Deformation within the SRSZ, in the study area, is partitioned into steeply south-dipping shear zones (where structures record non-coaxial shearing) that bound rock volumes wherein strain is recorded by systems of vertical, anastomosing shear zones that suggest a bulk pure shear. Within the SRSZ, rocks affected by bulk pure shear are deformed by anastomosing shear zones that are observed at the outcrop scale. Extension lineations within the anastomosing shear zones are vertical and the finite strain state tends to be constrictive (*see* Figure 18.4b). The partitioning of deformation within the SRSZ into non-coaxial shear zones that bound rock volumes where bulk pure shear is predominant is suggestive of a transpressive strain history; the northwest transport of the rocks in the hanging wall of the SRSZ may have been accommodated mainly by the non-coaxial shear zones whereas much of the SRSZ may have been affected by a bulk horizontal shortening accompanied by vertical extrusion. Interestingly, some sulphide mineralization seems to have a positive spatial relationship with the anastomosing shear zones, suggesting possible remobilization of sulphide mineralization during post-impact deformation.

An important observation arising mainly from our investigations of industry diamond-drill core is that footwall rocks are deformed, foliated and lineated, apparently due to the same deformation event that gave rise to the SRSZ. This interpretation is based on the parallellism between fabrics in rocks of the SIC (*see* Figure 18.3a) and rocks of the footwall (*see* Figure 18.3b) observed in the diamond-drill core.

Petrographic study of thin sections from the drill core is expected to confirm that the footwall rocks were involved in the ductile thrusting accommodated by the SRSZ, which may have resulted in imbrication of the footwall rocks with parts of the SIC.

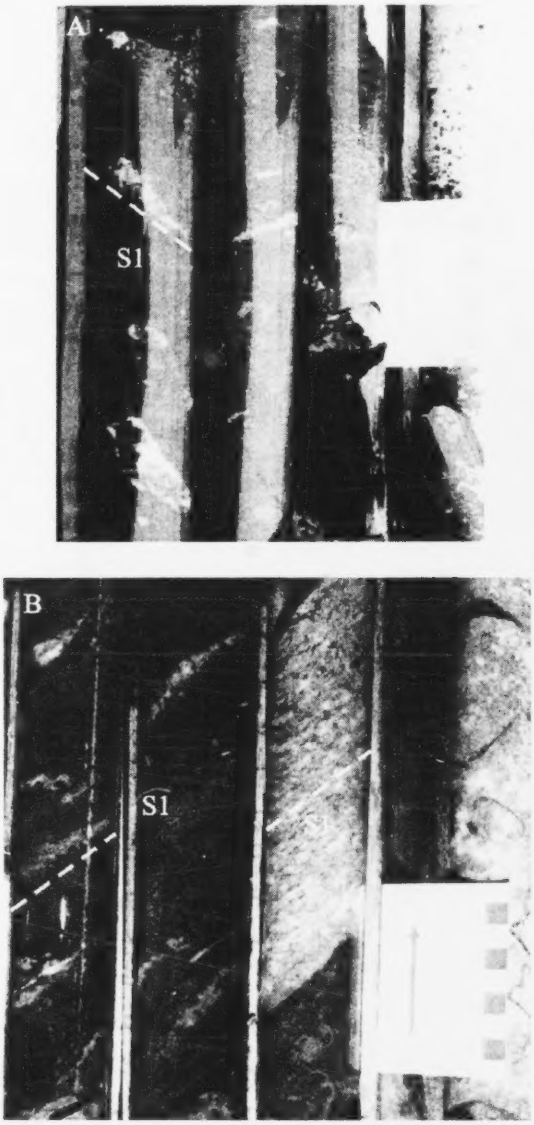


Figure 18.3. Foliation (S1) related to thrusting on the SRSZ, observed in core from one diamond drill hole. **a)** Foliated sublayer norite. **b)** Foliation in the footwall rocks, here composed of strongly deformed Neoarchean granite (light coloured) and greenstone (dark coloured) of the Superior Province. The arrow on the scale card points to the top of the almost vertical drill hole. The foliation dip is 50° to the southeast.

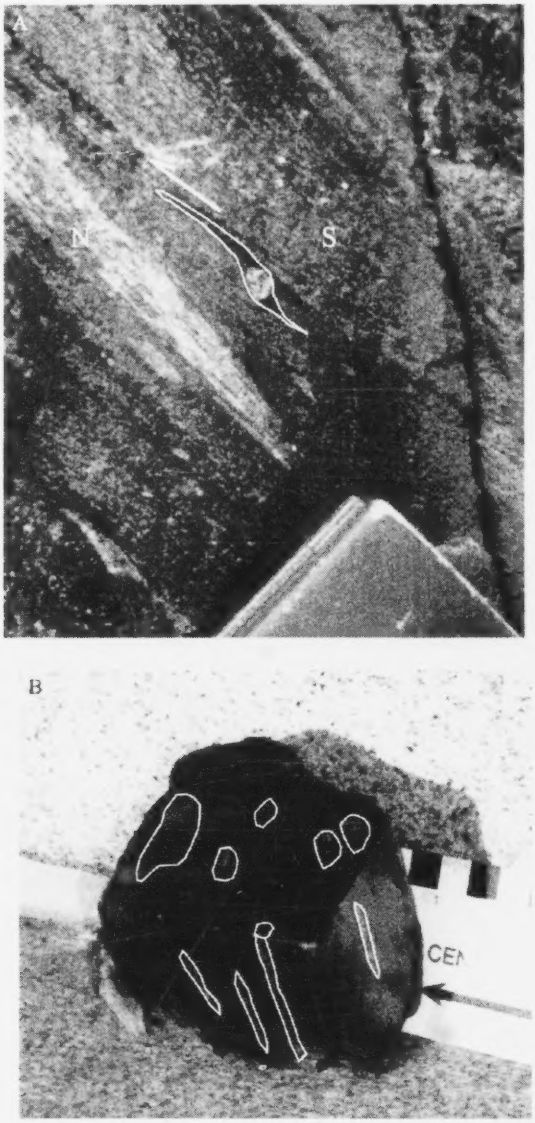


Figure 18.4. **a)** Clasts in the Onaping Formation observed on a vertical plane, displaying a reverse (south-over-north) sense of shear. **b)** Hand specimen from the Onaping Formation, where clast shapes suggest a constrictional bulk pure shear.

Crenulation of the main foliation in the SRSZ is observed in an outcrop close to the Victoria Mine. The foliation plane (here termed S_1) strikes 060° and is interpreted to be the result of SRSZ deformation. The foliation plane has been affected by S_2 crenulations striking 110 to 135° (Figure 18.5a). The origin of the S_2 crenulation has not been determined, however, we speculate that it may record late sinistral movements on faults in the study area.

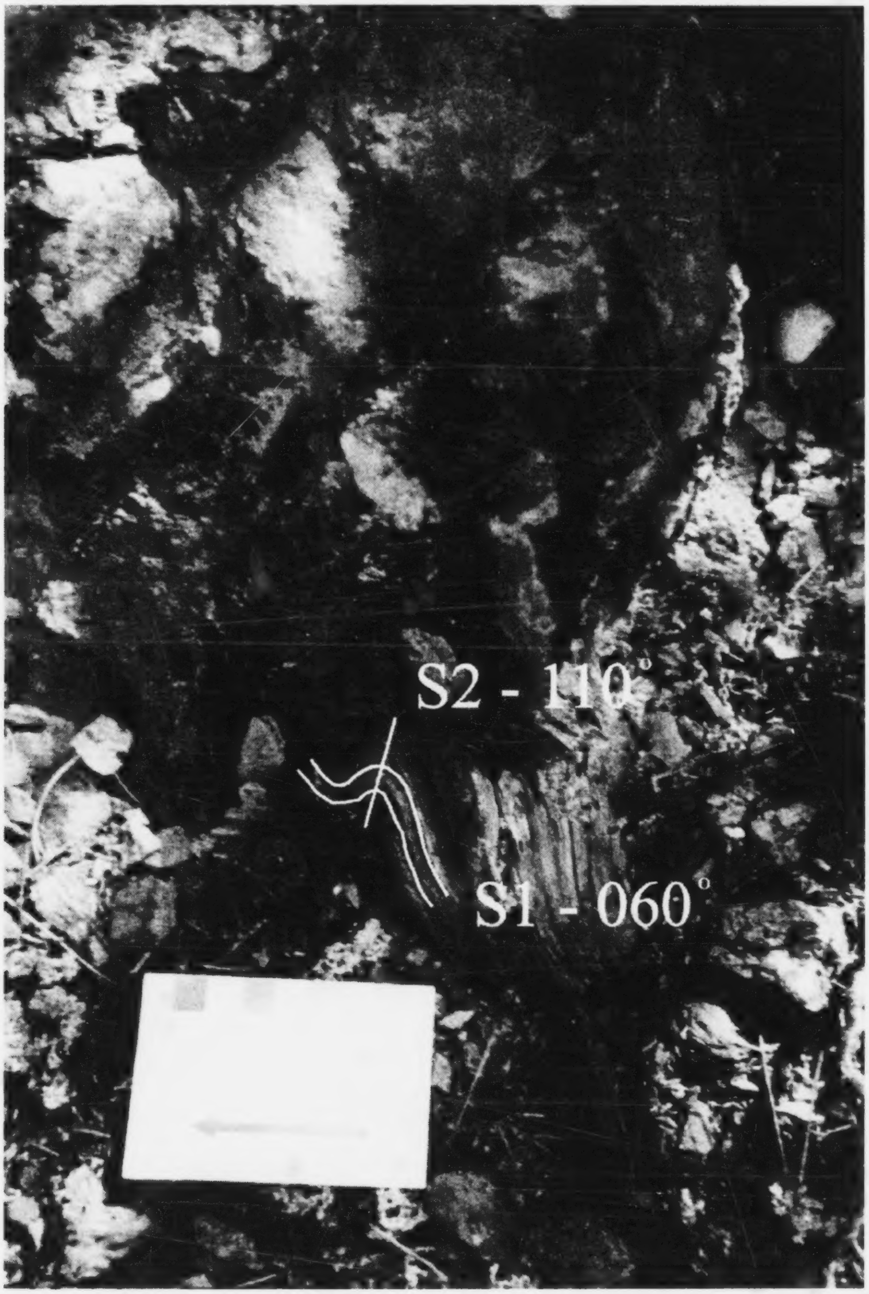


Figure 18.5. Crenulations of S_1 foliation planes in sulphide-rich rock, in the vicinity of the Victoria Mine. The arrow on the scale card points toward north.

Brittle Deformation

Brittle faulting is present in every outcrop in the study area. The brittle faults can be grouped into 3 main orientations: north-northeast-, northeast- and southeast-striking (A.J. Dubois and K. Benn, unpublished data, 2002). It is likely, that in the strongly foliated rocks of the SRSZ, the predominance of northeast-striking faults is related to reactivation of the foliation during brittle faulting. Field observations of slickensides and striations on fault planes indicate that normal, strike-slip and thrust kinematics were accommodated by different faults. Analysis of the stress fields associated with faulting was performed. Stress inversion from fault slip data indicates a northwest maximum compression direction (A.J. Dubois and K. Benn, unpublished data, 2002), which is consistent with the results of Cowan, Riller and Schwerdtner (1999).

IMPLICATIONS FOR MINERAL EXPLORATION

The present study area may be the most structurally complex part of the Sudbury Basin. Our extensive structural analyses will provide new constraints on the structural evolution of the study area , and on the geometries of the different rock units and major structures in the subsurface. The results will provide a better framework for mineral exploration in the southwestern part of the Sudbury Basin. Successful mineral exploration programs should, therefore, benefit from the structural analyses that are part of this study.

The ore bodies exploited within the southwestern Sudbury Basin are mainly situated within 2 types of geologic environments: 1) they are located at the contact between the SIC and the footwall; or 2) they occur in the quartz-dioritic offset dikes (Morrison, Jago and White 1992). Also, other ores may have been generated by post-impact hydrothermal events that remobilized and concentrated metals within the Sudbury Breccia (Watkinson 1994) and within the footwall. Thrusting associated with the SRSZ may have led to the imbrication of geological units as well as deformation of ore deposits and remobilization of metals. Our studies of diamond-drill core suggest that structural imbrication of the footwall–SIC contact may be extensive. Ongoing work will test this interpretation, which has implications for exploration, since ore deposits may also be strongly deformed and imbricated.

The compilation of an extensive database including the results of mapping and structural analysis; data gleaned from diamond-drill cores; and the incorporation of available geophysical data started in July 2001 (A.J. Dubois and K. Benn, unpublished data, 2002). The results will provide the basis for three-dimensional modelling of the subsurface geology, and for subsequent modelling of the structural evolution of the study area using the Noddy™ software package at the University of Ottawa.

CONCLUSIONS

During the 2 summers of field work, in 2001 and 2002, over 457 outcrops were mapped and extensive sampling was carried out for petrographic studies. Bedrock mapping and preliminary petrographic results lead us to recognize 3 structurally distinct zones within the study area. The most highly deformed zone, the SRSZ, appears to be bounded by the Cameron Creek and Cameron Lake faults on its northern side and by the Creighton fault on its southern side. To the north and the south of the SRSZ, the SIC is unstrained or only weakly strained, and the structures in the footwall rocks most likely record pre-SRSZ (and possibly pre-impact) tectonic events.

Structures, south of the SRSZ and in the Onaping Formation, suggest a bulk pure shear with a vertical maximum principal stretching direction. This structural framework suggests that ductile deformation after the "Sudbury event", in the study area, may have occurred in a transpressive regime, with simple shear partitioned into (mainly) dextral-reverse shear zones that may bound rock volumes wherein bulk pure shear was accommodated by a system of anastomosing shear zones.

Detailed studies have been undertaken on 8245 km of diamond-drill core belonging to INCO, Falconbridge Limited and FNX Mining Company. The data from drill logs and from our own re-logging of the core will be used to establish structural profiles in key parts of the study area. In 2002 to 2003, the data collected from bedrock mapping, the diamond-drill hole logs and available geophysical data will be used to constrain the geometries of the rocks and structures in the subsurface, so that a three-dimensional model of the study area may be constructed. Structural modelling software (Noddy^{TM}) will then be used to test possible kinematic models to explain the deformation after the "Sudbury event" in the western Sudbury Basin.

The results of the extensive mapping, petrographic studies, diamond-drill core logging and structural modelling should provide a new framework for targeting potential mineral exploration targets, and also for proposing models for the formation, and subsequent deformation of the Sudbury impact structure and its hosted mineral deposits. In particular, structural imbrication of the footwall rocks with parts of the SIC may prove to be of particular interest for mineral exploration programs.

ACKNOWLEDGMENTS

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19. Project Unit 02-044. A Predictive Model for Diamond-Bearing Rocks in Ontario

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INTRODUCTION

A comprehensive new approach for conducting mineral resource assessments was required in response to the implementation strategy for *Ontario's Living Legacy*, a large-scale land use planning initiative for public lands that will result in the creation of 378 new parks and protected areas in Ontario. Under the direction of the Ministry of Northern Development and Mines (MNDM), a committee consisting of representatives from government and various mineral sector client associations was established to develop a new process for qualifying Ontario's mineral potential. Several months of discussion and review of methods used previously in the province and in other jurisdictions led to a new process for assessing mineral potential based on a numerical index referred to as the Provincially Significant Mineral Potential (PSMP) methodology for conducting mineral resource assessments.

As with various other qualitative mineral resource assessment schemes, the PSMP methodology draws on our current knowledge and understanding of the province's geology, its mineral endowment and diagnostic attributes related to the various mineral deposit types that are found or may occur in Ontario. Our ever-expanding geoscience knowledge base and increased understanding of mineral deposit forming processes led to an inherent guiding principle in the PSMP methodology that calls for the ongoing, periodic review and revision of the criteria used in assessing mineral potential.

The committee that developed the PSMP methodology lacked technical expertise in the field of diamonds. Even after consulting diamond experts, the committee continued to struggle in developing what it considered to be an effective predictive model for diamond-bearing rocks. In the end, the committee settled on an approach based on the location of known kimberlites and other diamond-bearing occurrences found in Ontario. This approach, although acceptable, is limited in that it lacks an element of predictability that goes beyond that which is already known. Based on recent new knowledge and concepts and in keeping with the principle of revising the criteria used in the PSMP methodology where and when appropriate, the authors offer a new approach for the predictive modelling for diamondiferous rocks in Ontario.

PETROLOGY AND DIAMOND FORMATION

Diamonds are the high-pressure form of carbon, which is stable only at great depths (>150 km) within the mantle of the Earth. Diamonds are found in the crust within mantle-derived igneous rocks such as kimberlites and lamproites (Mitchell 1991) and, more rarely, hosted within lamprophyres (Jaques et al. 1989), alkali basalts and alpine-type peridotites (Kaminskii 1984). Formerly, diamonds were considered phenocrysts within kimberlites, however, Richardson et al. (1984) demonstrated that the Sm/Nd model

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age of inclusions within diamonds in the Cretaceous (90 to 100 Ma) Finsch and Kimberly kimberlites in the Archean Kaapvaal craton (South Africa) were 3300 Ma. These data established that diamonds are xenocrysts within kimberlites. The petrology of inclusions within diamonds reveals that diamonds formed at upper mantle temperatures and pressures (reviewed by Mitchell 1991). For example, diamonds within relatively young kimberlites and lamproites of the Archean Kaapvaal craton of South Africa have their origin within the underlying mantle at depths over 150 km. The diamonds are transported to the near-surface environment as xenocrysts (xenoliths) within mantle-derived magmas produced by melting of garnet harzburgite or eclogite. Diamond xenocrysts will be preserved only within products of magmas, which 1) originate at depths within or below the diamond stability field; 2) pass through the diamondiferous zones of the mantle; and 3) do not oxidize diamond inclusions and ascend rapidly through to the crust, thus preserving the diamonds as meta-stable inclusions.

The major rock types fulfilling the above criteria are kimberlites and lamproites. Generally, diamondiferous kimberlites occur within Archean cratons (Clifford 1966), and are best preserved in cratons with undeformed Phanerozoic cover sequences in which the kimberlites are intruded. Kimberlites are generally found within "fields" approximately 50 to 100 km in diameter (Kaminsky et al. 1995) that contain groups of kimberlite pipes. Mitchell (1991) asserts that kimberlites "show no relation to known rift zones", but can be related to "linear or arcuate trends" possibly related to major crustal fractures. This is illustrated with the proposed kimberlite–lineament association of Arsenyev (1962) and Bardet (1965). However, Kaminsky et al. (1995) and Serokurov, Kalmykov and Smirnova (1995) note that Russian pipes in "fields" can be disposed about minor structural domes. Lamproites occur along the margins of cratons or in accreted Proterozoic mobile belts, such as the Halls Creek mobile belt surrounding the Archean Kimberly craton (White, de Boorder and Smith 1995). Thus, the location of kimberlite fields and perhaps lamproites may be controlled by regional-scale structures that facilitate the ascension of kimberlitic or alkaline magma (White, de Boorder and Smith 1995; Card, Sanford and Card 1997).

To better understand the possible place of kimberlites in the structural evolution of the Superior Province, we trace the Archean cratonization and subsequent structural and intrusive history of the Superior Province. Boundaries between individual Archean terranes and/or superterranes develop during juxtaposition of terranes in the Kenoran orogeny. Where there are promontories in the outline of terranes, indentor tectonics produce escape structures, for example, where the Winnipeg River Subprovince has impinged upon the English River Subprovince. The northward movement of the Winnipeg River Subprovince produced southwest- and southeast-trending structures of Neoarchean age in rocks to the north. Examples include the Gravel River and the Miniss River faults. After cratonization and related crustal thickening, the Superior Province has undergone episodic reactivation, manifested by development of Proterozoic faulting and intrusion by several generations of carbonatite-alkalic rock complexes (Sage 1991) and about 12 diabase dike swarms ranging in age from 2.5 Ga to 1.1 Ga (Osmani 1991). The diabase dikes vary in orientation and age and represent response to variably oriented stress fields in the Proterozoic. Manson and Halls (1997) examined variation in the Rb/Sr, K/Ar and Ar/Ar ages on biotite in diabase dikes across the Superior Province relative to hornblende ages on the same dikes. Hornblende ages range from 2.4 to 2.6 Ga, whereas biotite ages range from 1.8 to 2.6 Ga. The eastern boundary of the disturbed biotite ages is marked by northeast-trending Archean and Proterozoic structures, including the Kapuskasing Structural Zone, the Gravel River fault and the Miniss River fault. These authors suggest this isotopic disturbance is likely caused by Proterozoic uplift. Thus, Archean cratonization and Proterozoic reactivation of those structures, as well as production of new Proterozoic structures, reflected in the age and orientation of diabase dikes and their reactivation testify to continuing development of major structures throughout Precambrian and Phanerozoic time.

CONTROLS ON ALKALINE MAGMATISM

Considering that kimberlites and lamproites are volatile-rich, mantle-derived alkaline magmas, Moorhead et al. (1999) asserted that identification of large-scale controls on the distribution of other alkaline magmas, such as carbonatites, may shed light on large-scale controls on kimberlite and lamproite magmatism. Sage (1991) indicated that carbonatite-alkalic rock magmatism in the Superior Province is controlled by regional-scale structures, which include the Trans–Superior Tectonic Zone, the Kapuskasing Structural Zone and the Ottawa–Bonnechere graben (Figures 19.1 and 19.2). Therefore, we conducted a GIS (geographic information system) mapping exercise that utilized data on the carbonatite-alkalic rocks of Ontario. On Figure 19.3, we plotted all Ontario carbonatite-alkalic rocks, which had ages determined previously, from Sage (1991, *see also* Table 18.2). Table 19.1 shows the carbonatites, with ages, together with the structure with which we interpret any given carbonatite to be spatially associated. Note that many additional carbonatites, without radiometric ages, are associated with these structures (Sage 1991) and that this association of given carbonatites with particular structures may differ from previous interpretations, such as Sage (1991).

The following observations may be drawn from Figure 19.3.

1. Archean terrane boundaries are spatially associated with Archean syenite and sanukitoid suite intrusions and Archean through Phanerozoic carbonatite and related rocks. The alkaline magmatism occurs near
   a. Boundaries between major Archean terranes, such as the Island Lake (~2.8 Ga) and the North Caribou terrane (3 Ga) boundary, which is the site of the Archean Wapikopa complex, the Mesoproterozoic Big Beaverhouse and Schryburt Lake alkaline complexes; the Winnipeg River terrane (3 Ga) – western Wabigoon terrane boundary (2.7 Ga); the site of the Archean Sturgeon Narrows and Squaw Lake intrusions; and the Kenyon structure forming the boundary between the Northern Superior Superterrane and the Oxford – Stull Lake terrane is the site of the Paleoproterozoic Carb Lake intrusion.
   b. Major Archean assemblage boundaries, such as the Porcupine–Destor deformation zone, the Larder–Cadillac deformation zone, are the site of Neoarchean alkaline and sanukitoid magmatism. This includes alkaline volcanism associated with Timiskaming pull-apart basins and alkaline syenite of the sanukitoid suite, such as the Otto stock at Kirkland Lake.

   All Archean terrane boundaries display evidence of Neoarchean sanukitoid suite monzodiorite to syenite bodies. Note that neither the Herman Lake complex nor the Poohbah Lake complex of Archean age appear to be associated with a terrane boundary. The Wapikopa Lake intrusion may be associated with a cryptic north boundary to a subdivision of the North Caribou terrane. Thus, Archean boundaries were subject to Archean, Paleoproterozoic, and Mesoproterozoic magmatism and reactivation (*see* Table 19.1).

2. Paleoproterozoic terrane boundaries and associated alkaline complexes are as follows:
   a. The rifting of the Superior craton, circa 2.48 Ga, associated with the East Bull Lake intrusive suite of mafic and ultramafic units is spatially, but likely not genetically, associated with the Seabrook Lake (Mesoproterozoic age) and Spanish River (Paleoproterozoic) complexes.
   b. The Kapuskasing Structural Zone was uplifted circa 1.9 Ga. Associated with it are alkaline complexes ranging in age from the Hecla–Kilmer complex (450 Ma) to the Borden complex (1894 Ma) with most bodies having Mesoproterozoic ages.

3. Mesoproterozoic structures are represented by the Midcontinent Rift and the Trans–Superior Tectonic Zone. Associated with these structures are the Dead Horse Creek diatreme, Killala Lake, Port Coldwell, and Prairie Lake alkalic complexes.
4. Paleozoic structures are dominated by the Ottawa–Bonnechere graben that extends up the Ottawa River valley at least as far as Lake Timiskaming and its eastward branch extending to the Lake Nipissing area. The Ottawa–Bonnechere graben has spatially associated alkaline intrusions near North Bay (Manitou Island) and at Brent.

Major structures, that is, terrane boundaries and rifts of Archean through Phanerozoic age, therefore, are spatially and genetically associated with carbonatite-alkalic rock magmatism.

Table 19.1. Carbonatite and alkalic rock complexes in Ontario and associated structures.

	Complex Name	Age (Ma)*	Structure
ARCHEAN			
	Herman Lake	Archean	?
	Poohbah Lake	2706	Quetico
	Sturgeon Narrows	2746	Wabigoon – Winnipeg River boundary
	Wapikopa	2534	Island Lake– North Caribou boundary
	Squaw Lake	Archean	Wabigoon – Winnipeg River boundary
PALEOPROTEROZOIC			
	Argor Township (?)	1950	Kapuskasing
	Borden Township	1894	Kapuskasing
	Carb Lake	1826	Kenyon
	Cargill Township	1906	Kapuskasing
	Goldray Township (?)	1884	Kapuskasing
	Spanish River	1838	Alkaline dike
	McKellar dikes	1653	Midcontinent Rift
MESOPROTEROZOIC			
	Big Beaverhouse	1109	Island Lake – North Caribou
	Chipman Lake	1029	Trans–Superior Zone
	Clay Howells	1072	Kapuskasing
	Dead Horse Creek	Mesoproterozoic	Trans–Superior Zone
	Firesand River	1008	Midcontinent Rift
	Killala Lake	1098	Midcontinent Rift
	Lackner Lake	1092	Kapuskasing
	Nemegosenda Lake	1015	Kapuskasing
	Port Coldwell	1108	Midcontinent Rift
	Prairie Lake	1165	Trans–Superior Zone
	Schryburt Lake	1145	Island Lake – North Caribou
	Seabrook Lake	1092	Kapuskasing
	ShenangoTownship	1047	Kapuskasing
	Teetzel Township	1155	Kapuskasing
	Valentine Township	Mesoproterozoic	Kapuskasing
	Nagagami River	Mesoproterozoic	Kapuskasing
	Martison Lake	Mesoproterozoic	Kapuskasing
CAMBRIAN			
	Brent Township (?)	414	Ottawa–Bonnechere
	Hecla–Kilmer Township (?)	450	Ottawa–Bonnechere
	Manitou Island	560	Ottawa–Bonnechere
	Newman Island	570	Ottawa–Bonnechere

*All ages listed are Rb/Sr and K/Ar determinations *from* Sage (1991).

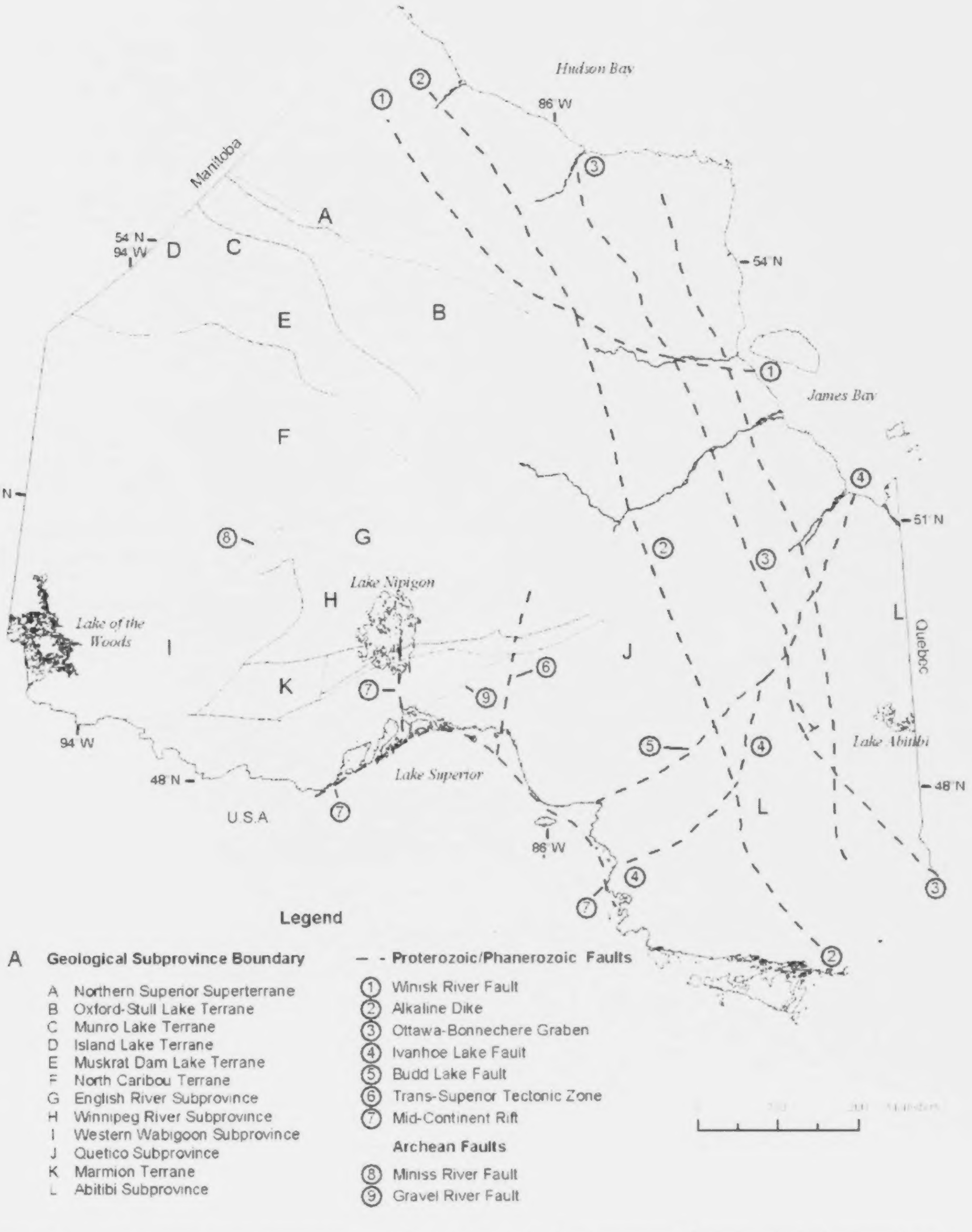
Hudson Bay
86°W
Manitoba
A
54°N
94°W
D
C
B
E
54°N
James Bay
F
51°N
G
51°N
Lake Nipigon
H
Lake of the Woods
I
J
L
Quebec
K
Lake Abitibi
94°W
48°N
Lake Superior
48°N
U.S.A.
86°W
L
①
②
③
④
⑤
⑥
⑦
⑧
⑨
Legend
A Geological Subprovince Boundary
A Northern Superior Superterrane
B Oxford-Stull Lake Terrane
C Munro Lake Terrane
D Island Lake Terrane
E Muskrat Dam Lake Terrane
F North Caribou Terrane
G English River Subprovince
H Winnipeg River Subprovince
I Western Wabigoon Subprovince
J Quetico Subprovince
K Marmion Terrane
L Abitibi Subprovince
– - Proterozoic/Phanerozoic Faults
① Winisk River Fault
② Alkaline Dike
③ Ottawa-Bonnechere Graben
④ Ivanhoe Lake Fault
⑤ Budd Lake Fault
⑥ Trans-Superior Tectonic Zone
⑦ Mid-Continent Rift
Archean Faults
⑧ Miniss River Fault
⑨ Gravel River Fault

Figure 19.1. Major Archean terrane boundaries, Archean faults, and rift-related structures of Proterozoic to Phanerozoic age. This subdivision of the Superior Province, particularly north of the English River Subprovince, is based upon Thurston (2002) and personal communication from K.Y. Tomlinson (2002). The subdivisions are tentative pending completion of the OGS component of Natmap and other projects. Note that the Kapuskasing Structural Zone, a circa 1.9 Ga intracratonic thrust, is bounded on the east by the Ivanhoe Lake fault and on the west by the Budd Lake fault.

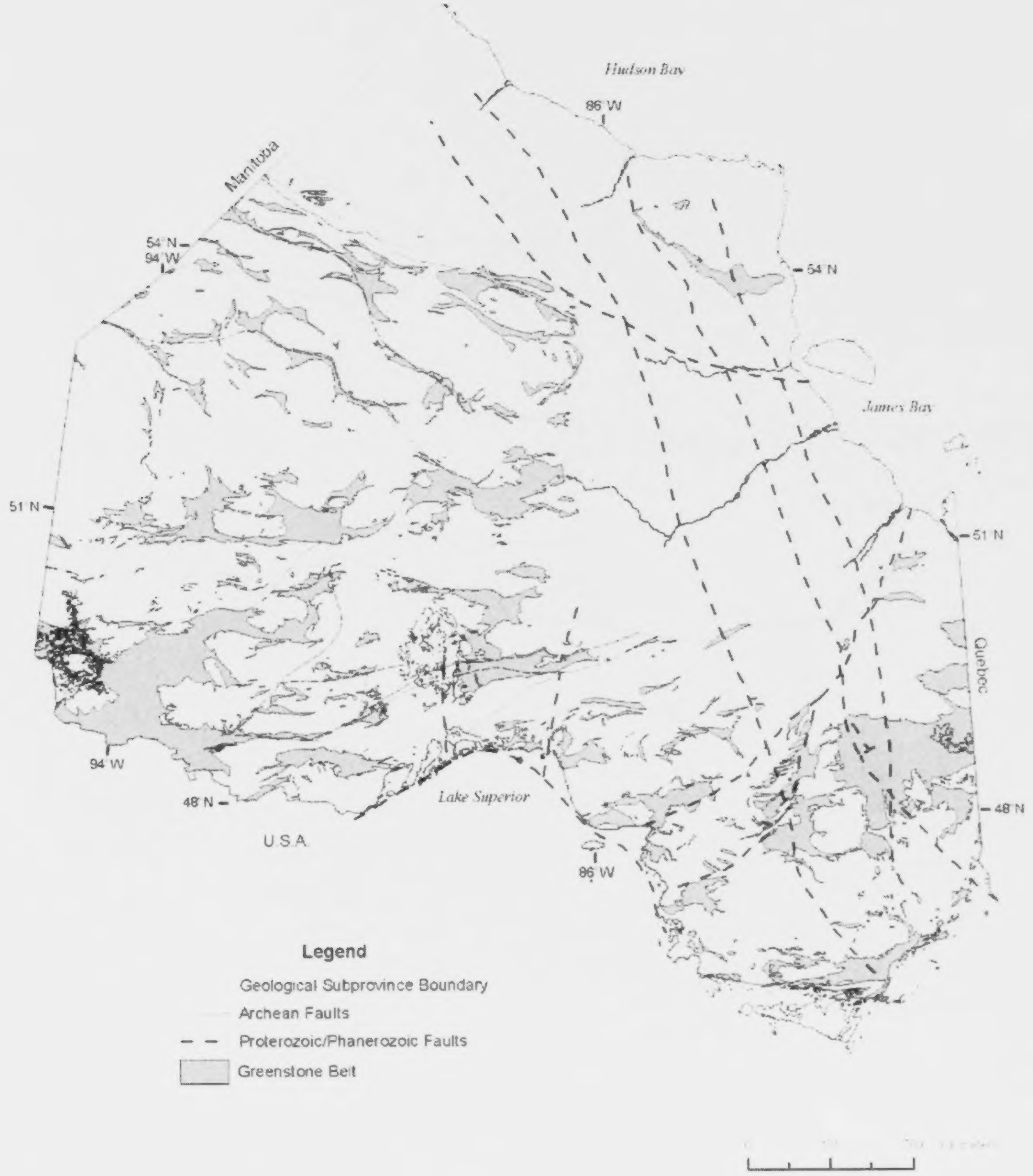
Hudson Bay
86°W
Manitoba
54°N
94°W
54°N
James Bay
51°N
51°N
Quebec
94°W
48°N
Lake Superior
48°N
U.S.A.
86°W
Legend
Geological Subprovince Boundary
Archean Faults
– – Proterozoic/Phanerozoic Faults
Greenstone Belt

Figure 19.2. Structures as shown in Figure 19.1 and major greenstone belts of Ontario.

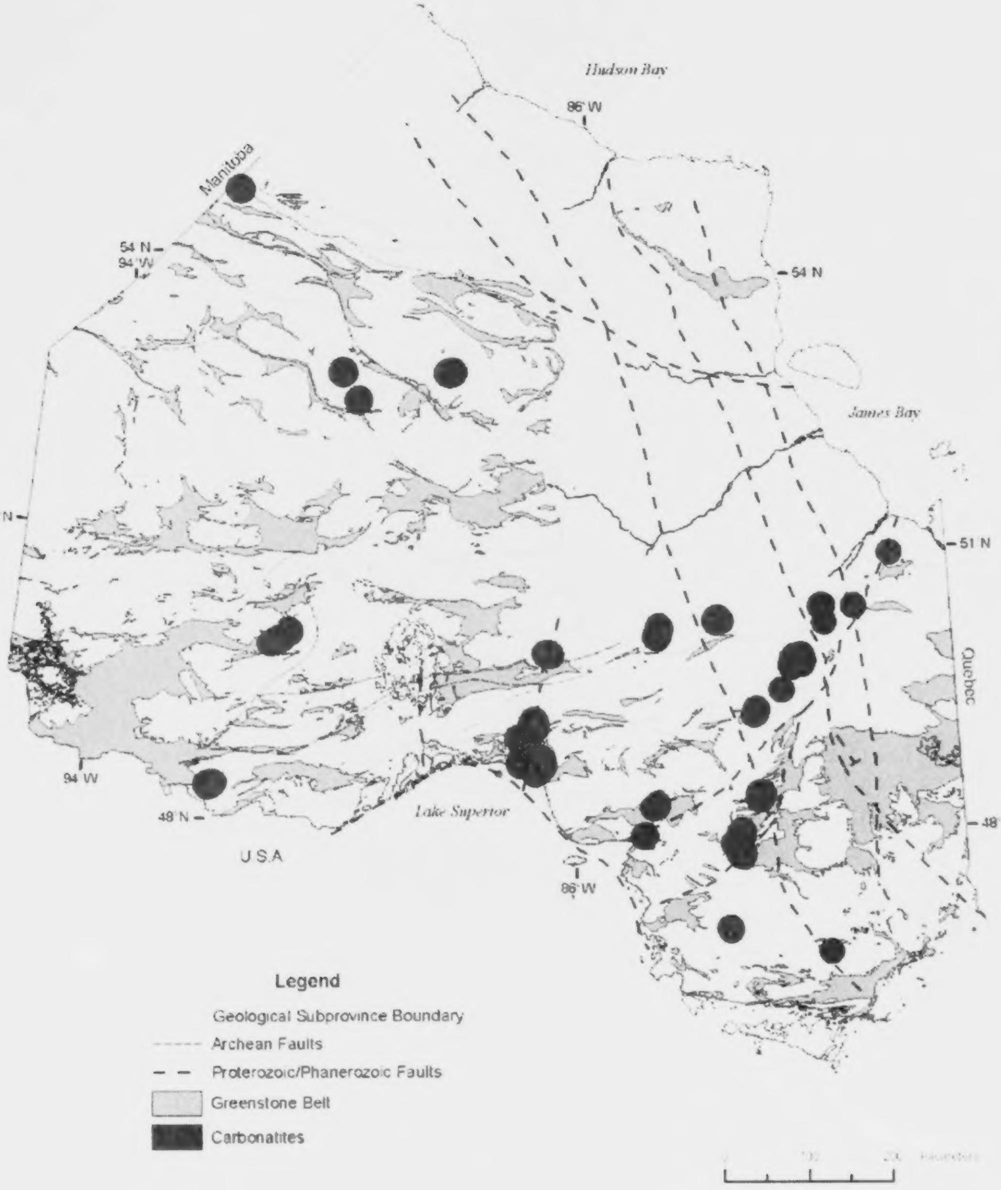
Hudson Bay
86°W
Manitoba
54 N
94 W
54 N
James Bay
51 N
51 N
Quebec
94 W
48 N
Lake Superior
48 N
U.S.A
86 W
Legend
Geological Subprovince Boundary
Archean Faults
Proterozoic/Phanerozoic Faults
Greenstone Belt
Carbonatites

Figure 19.3. Location of carbonatites and alkalic-rock complexes in Ontario, with known ages. Complexes with age determinations are *from* Sage (1991). All carbonatite-alkalic rock complexes are shown with the same symbol, regardless of age.

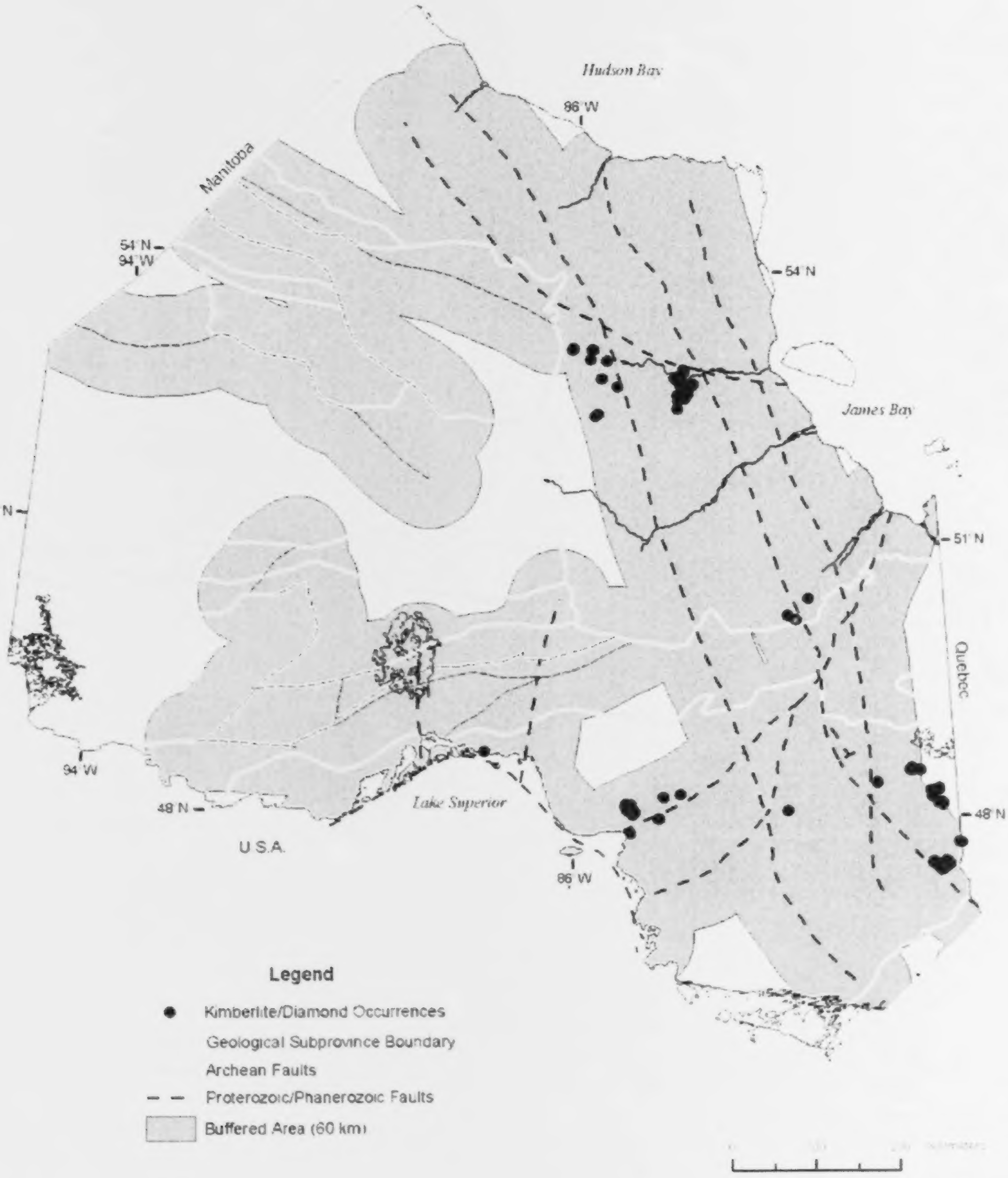
Hudson Bay
86°W
Manitoba
54°N
94°W
54°N
James Bay
51°N
51°N
Quebec
94°W
48°N
Lake Superior
48°N
U.S.A.
86°W
Legend
● Kimberlite/Diamond Occurrences
Geological Subprovince Boundary
Archean Faults
– – Proterozoic/Phanerozoic Faults
Buffered Area (60 km)
0
100
200
Kilometers

Figure 19.4. Location of kimberlites and diamond occurrences in Ontario based upon Sage (1996, 2000a, 2000b) and the MDI II database. Note the 60 km buffer around major structures.

CONTROLS ON DIAMOND-BEARING ROCK TYPES

There is a spectrum of opinion on structural control of kimberlites (e.g., Mitchell 1991; White, de Boorder and Smith 1995; Helmstaedt 1993; Moorhead et al. 1999) ranging from little control to detailed exposition on major and minor structures and their influences. There are several kimberlites and related rocks within Ontario (Sage 1996, 1997, 2000a, 2000b), as well as recently discovered diamandiferous lamprophyre dikes and ultramafic pyroclastic rocks (Kivi and Walker 2002) in the Wawa area. In the light of these recent discoveries, we viewed establishing a predictive model for diamond-bearing rocks to be important, given the increasing amount of land being removed from the mineral exploration land base through land use planning initiatives, such as the *Ontario's Living Legacy*. To develop the predictive model, we here compare the spatial associations of diamondiferous units with other types of alkaline magmatism. We compiled geographic location information on all Ontario kimberlite and diamond occurrences from Sage (1996, 2000a, 2000b) and from the MNDM Mineral Deposit Inventory (MDIII) database of kimberlites and/or diamond occurrences (Figure 19.4) to review structural controls given the suggestions of Sage (1998).

Sage (1998) suggested that diamond occurrences and kimberlites, other than those near Wawa, occur along a 325° "trend" with individual pipes and clusters related to more local faults, "linears" and lithologic contacts (*see also* White, de Boorder and Smith 1995). Sage (1998) related kimberlite pipes in the New Liskeard and Kirkland Lake area to the "Lake Timiskaming Structural Zone". Pipes of Jurassic age in the Hudson Bay Lowlands were described as "near" the Winisk River fault, although no overt control by this structure is suggested (Sage 1998). Our analysis (*see* Figure 19.4) suggests that Ontario kimberlites are spatially associated with the following features:

1. the Kirkland Lake and New Liskeard kimberlites are associated with Ottawa–Bonnechere graben and its extension through to Lake Timiskaming (Sage 1998).
2. The Mesozoic Attawapiskat kimberlites are associated with a northern extension of the Ottawa–Bonnechere graben and are also similar in trend to nearby dikes of the Marathon dike swarm (circa 2.2 Ga). We suggest here that the Ottawa–Bonnechere graben extends north of Lake Timiskaming (Gupta 1991a, 1991b) on the basis of north- to north-northwest-trending magnetic features in the vicinity of the carbonatites (*see* Figure 19.3) and kimberlites (*see* Figure 19.4) on the Moose River to the kimberlites near Attawapiskat.
3. The Proterozoic Kyle kimberlites are disposed on either side of a north-trending aeromagnetic low described by Thurston and MacFadyen (1992) as extending north and south from the vicinity of the carbonatites in the James Bay Lowlands to the Kyle kimberlites of Sage (2000b). Thurston and MacFadyen (1992) considered the aeromagnetic low to be an alkaline dike based on its lateral extent, the fact it crosscuts Archean structures, the low magnetic susceptibility and its spatial association with carbonatites. They suggested that the dike is mineralized by alkaline fluids like similar dikes in the Brazilian Shield (Svisero, Meyer and Tsai 1979; Barbosa 1991). Alternatively, the aeromagnetic low could equally well represent later alkaline magmatism reactivating fractures related to McKenzie–Sudbury swarm diabase (1.2 Ga).
4. The kimberlite in the Wawa area is spatially associated with the fault system forming the east boundary of the Kapuskasing Structural Zone termed the Budd Lake fault.

The recently discovered diamondiferous pyroclastic units in the Wawa area (Kivi and Walker 2002) are spatially confined to the Catfish assemblage (2750 Ma) (Williams et al. 1991) and, based upon reconnaissance by the senior author and A. Wilson (District Geologist responsible for the Wawa area), are metamorphosed and, thus, probably Archean in age. The units have structural trends similar to the Catfish assemblage and, thus, are likely part of that assemblage, although their alkaline affinity is also consistent with the alkaline volcanism typical of Timiskaming equivalent units, such as the Doré assemblage.

THE PROVINCIALLY SIGNIFICANT MINERAL POTENTIAL MODEL FOR KIMBERLITES AND DIAMOND MINERALIZATION

The current Provincially Significant Mineral Potential (PSMP) model for kimberlites relies primarily on the location of known kimberlites and on the observation that kimberlites tended to occur in clusters. The model, therefore, utilizes a buffer with a 30 km radius around known kimberlites and designates that the inscribed area within the 30 km radius as having elevated potential for the occurrence of additional kimberlites. We conclude through this GIS analysis that kimberlites and carbonatites are spatially and possibly genetically associated with major structures. These structures include Archean terrane boundaries, such as those enumerated above, that are spatially associated mainly with carbonatites and Proterozoic and Phanerozoic structures spatially associated with kimberlites. This fault association with alkaline magmatism may also be operative for the Proterozoic lamprophyres in the Lake Superior region. However, there is no clear explanation for the diamondiferous pyroclastic units in the Wawa area. Similar units are found in the Cobalt area (G. Grabowski, District Geologist, Kirkland Lake, personal communication, 2002). We consider the Michipicoten greenstone belt to be a western extension of the Abitibi greenstone belt in terms of the ages of major units, structural and geochemical patterns (Williams et al. 1991). The sole unusual feature of this greenstone belt, relative to the Abitibi greenstone belt, is the presence of a sliver of crust with an age of 2.89 Ga and, thus, we suspect that the diamondiferous pyroclastic units may be related to thickened crust beneath this older fragment in the Michipicoten greenstone belt.

Therefore, a revised predictive model for the occurrence of kimberlites and diamond mineralization suitable for the PSMP process would involve

1. identification of major Archean and younger major faults forming terrane boundaries or rifts; and/or the trend of Proterozoic dike swarms relatable to alkaline magmatism,
2. establishment of the spatial distribution of kimberlites, diamond occurrences and carbonatite-alkalic rock associated with the above structures; and
3. erection of a corridor of sufficient breadth on both sides of these major structures apparently controlling alkaline magmatism to include the bulk of the occurrences of alkaline magmatism, especially kimberlites.

We note that a corridor extending 60 km on both sides of the major structures identified in this study (*see* Figures 19.3 and 19.4) encompasses the known kimberlite and diamond occurrences with one exception. Therefore, we recommend that, in the PSMP process, this 60 km wide corridor of elevated potential for future kimberlite discoveries be employed. The exception is diamondiferous pyroclastic units at Wawa and Cobalt. We believe that this type of mineralization is best protected by identification of potential host rocks of alkaline affinity within zones of anomalously thick lithosphere. This identification can be made indirectly by identification of fragments or terranes of crust with an age older than 2.75 Ga. Areas of the Superior Province with the crustal fragments older than 2.75 Ga show evidence of isotopic inheritance suggesting the presence of thicker than normal crust (Thurston 2002 and references therein).

Given the evidence enumerated above, we recommend establishing a revised predictive model for the occurrence of diamondiferous rocks in Ontario based mainly upon fault control. We recognize that there is no consensus on the geotectonic controls on kimberlites (reviewed by Helmstaedt 1993). However, given the degree of fault control on other types of alkaline magmatism enumerated above, we recommend that the predictive model for diamond-bearing rocks as presented above should be used in the PSMP methodology for mineral resource assessments until such time as a clearer picture of geotectonic controls emerges.

ACKNOWLEDGMENTS

We are indebted to exploration industry colleagues who shared their ideas on diamond mineralization during the deliberations of the PSMP committee. It was through that process that we realized we needed to improve our knowledge of possible controls on kimberlite magmatism. We are also indebted to our colleagues in Géologie Québec who shared with us both published and unpublished material. The background provided by that interchange has been very helpful. Several geologists in the diamond industry have provided background knowledge, but the authors remain solely responsible for the material herein. We also acknowledge the field trip provided by Ann Wilson of the Resident Geologist Program to the diamondiferous pyroclastic and dike units of the Wawa area. Dr. Greg Stott of the Precambrian Geoscience Section, Ontario Geological Survey, discussed a previous version of this manuscript with us and generously provided his thoughts on the importance of Proterozoic reactivation and the possible role of diabase dike swarms.

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Sedimentary Geoscience Section

20. Project Unit 02-013. Aggregate Resources Inventory Compilation of the Oak Ridges Moraine, Southern Ontario

S. Douglas

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INTRODUCTION AND BACKGROUND

The Oak Ridges Moraine (ORM) is a large, stratified moraine complex located in southern Ontario that stretches 160 km from the Niagara Escarpment in the west to Northumberland County in the east (Figure 20.1). The moraine forms a ridge of sand and gravel and is a prominent glacial feature in southern Ontario (Chapman and Putnam 1984). The ORM crosses and is found in parts of 4 counties (Dufferin, Northumberland, Peterborough and Simcoe), 3 regional municipalities (Durham, Peel and York), and the City of Kawartha Lakes. Approximately 65% of the ORM area lies within the Greater Toronto Area (GTA). Due to the close proximity of the ORM to market and wealth of sand and gravel resources, the moraine is one of the main aggregate sources for the GTA.

Aggregate Resources Inventory Papers (ARIPs) produced by the Ontario Geological Survey (OGS) provide coverage of the ORM (*see* Figure 20.1). Differences exist, however, in the extent of coverage provided by the ARIPs. Between 1979 and 1995, ARIPs were produced on a township basis (OGS 1980, 1985, 1992a, 1992b, 1994; Rowell 1997) and, hence, aggregate resources were assessed on a township by township basis. In some cases, this resulted in aggregate-poor townships having lesser quality or small deposits selected for planning protection when larger, higher quality deposits in adjacent townships were not identified for protection.

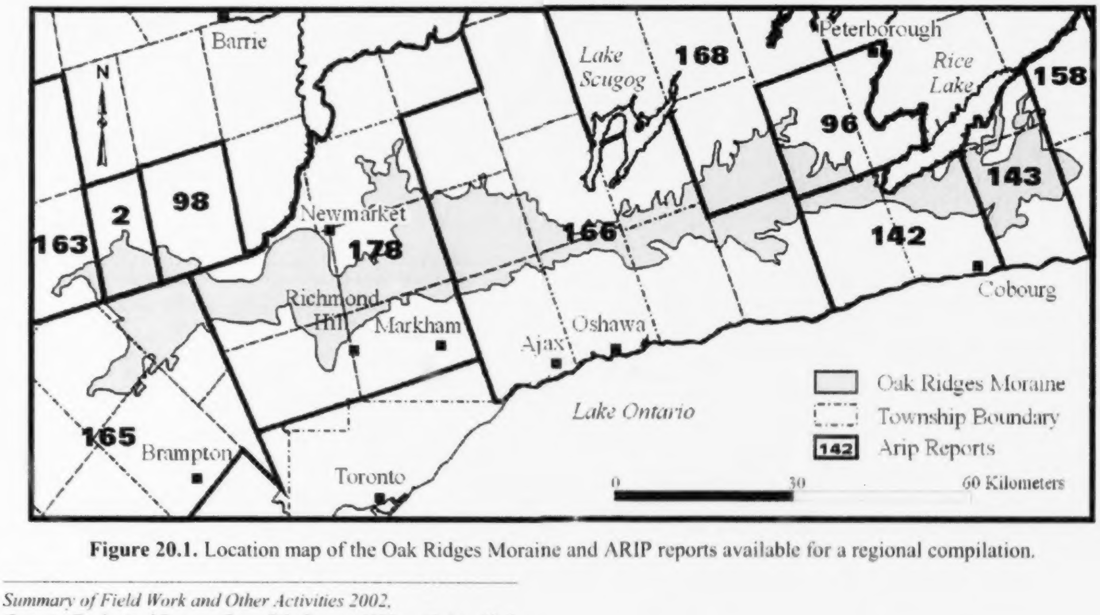
Barrie
N
Lake Scugog
168
Peterborough
Rice Lake
158
96
143
2
98
163
Newmarket
178
166
142
Cobourg
Richmond Hill
Markham
Ajax
Oshawa
Oak Ridges Moraine
Township Boundary
142
Arip Reports
Lake Ontario
165
Brampton
Toronto
0
30
60 Kilometers

Figure 20.1. Location map of the Oak Ridges Moraine and ARIP reports available for a regional compilation.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.20-1 to 20-3.

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Table 20.1. List of ARIPs covering the Oak Ridges Moraine.

ARIP No.	Abbreviated Title	Publication Year
	Township Coverage	
2	ARIP of Adjala, Simcoe County	1980
96	ARIP of Cavan, North Monaghan and South Monaghan, Peterborough County	1985
98	ARIP of New Tecumseth, Simcoe County	1992
142	ARIP of Hope and Hamilton, Northumberland County	1994
143	ARIP of Haldimand and Alnwick, Northumberland County	1992
158	ARIP of Brighton, Cramahe, Murray, Percy and Seymour, Northumberland County	1997
	Regional and/or County Coverage	
163	ARIP of Dufferin County	1998
165	ARIP of Regional Municipality of Peel	1996
166	ARIP of Regional Municipality of Durham	1999
168	ARIP of Victoria County	2000
178	ARIP of Regional Municipality of York	in progress

This disparity, combined with the continued extraction activities (pit depletion), an expressed desire by clients for regional level and digital map coverage, and the availability of new geological data and maps (Barnett and McCrae 1996; Barnett, Dodge and Henderson 1996; Gorrell and Brennand 1997) provided the impetus for the switch to regional mapping programs in the middle to late 1990s (Kelly and Rowell 1995).

Due to the demand for up-to-date aggregate resource information in the GTA, several regions and/or counties covering parts of the ORM, were selected for consolidation and updating of the township ARIPs. Regional ARIP reports were produced for the Regional Municipalities of Durham and Peel (Golder Associates Limited and Rowell 1996; OGS and MacNaughton Hermsen Britton Clarkson Planning Limited 1998); the County of Dufferin (MacNaughton Hermsen Britton Clarkson Planning Limited and OGS 1999); Victoria County (Geomatics International Limited and Rowell 2000); and the Regional Municipality of York (Gao 2001). Presently, a mix of township and recent regional ARIP reports cover the ORM (*see* Figure 20.1; Table 20.1).

PRESENT PROJECT

The ORM is currently undergoing a land use planning review in support of the *Oak Ridges Moraine Protection Act, 2001*. In order to provide information for the planning process and to provide input to the municipalities affected by this Act, the OGS has initiated a project to consolidate all of the ARIPs along the ORM. The purpose of the field work associated with this project was to

- collect additional field data;
- resolve "boundary faults" (map edge differences) between adjacent county and township ARIPs;
- standardize the classification of aggregate deposits and ARIP Selected Resource Areas along the ORM.

The final product of the study will be a digital compilation of the aggregate resources for the Oak Ridges Moraine. This compilation is designed to aid the planning process along the Oak Ridges Moraine. It will be of interest to various government agencies, aggregate producers, planners and other clients.

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21. Project Unit 02-016. Aggregate Resources Inventory of the County of Grey, Ontario

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INTRODUCTION

The Sedimentary Geoscience Section, in partnership with the County of Grey, is undertaking an aggregate resources inventory for Grey County (Figure 21.1). The work will update the 16 existing Aggregate Resources Inventory Papers (ARIPs) that cover the county. Each of the existing ARIPs covers a single township; the exception being the grouping of Keppel and Sarawak townships in a single publication. The township boundaries of the ARIP studies are those that were in existence prior to municipal amalgamations that have taken place over the past number of years.

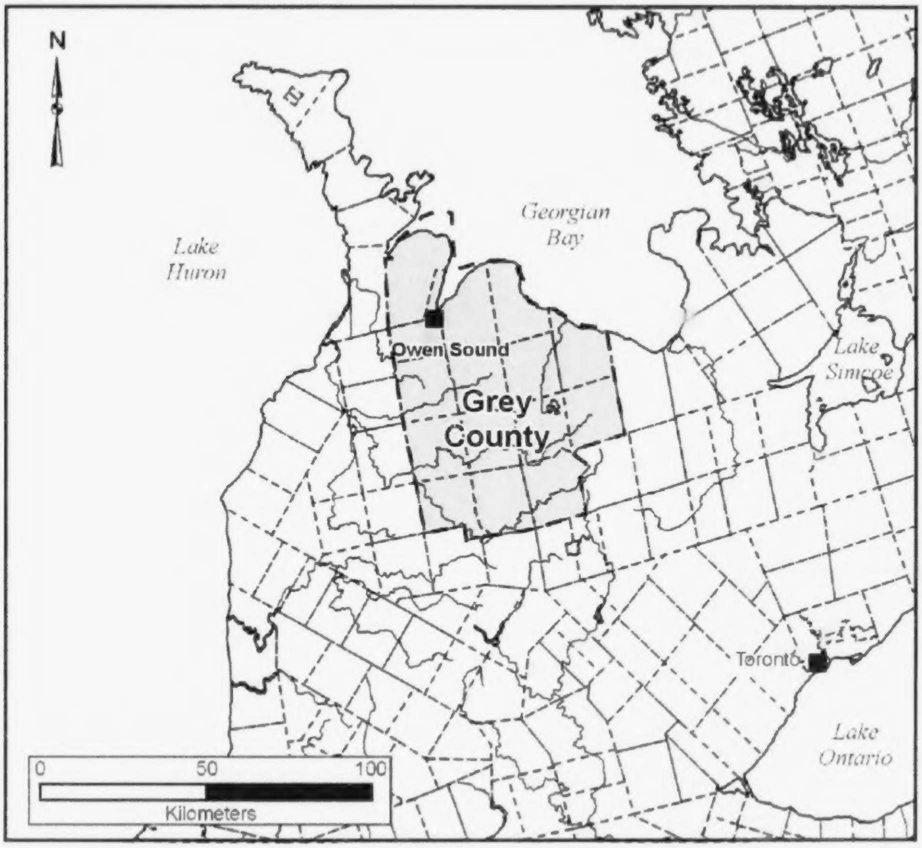

Figure 21.1. Location of Grey County. The updated aggregate inventory being produced will provide county-wide coverage and replace the 16 existing ARIP reports.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.21-1 to 21-3.

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The current aggregate inventory is being completed as part of a larger land use planning study being undertaken by the Country of Grey. This study, termed the Aggregate Resources Master Plan (ARMP), is working towards protecting and managing provincially significant aggregate resources to ensure that the public interest is being met. The purposes of the ARMP are multifold:

- to identify and examine the mineral aggregate resource(s) in the County of Grey;
- to assess the environmental, social and economic factors affecting resource utilization;
- to develop a management strategy for aggregate resources and rehabilitation of future and existing extracted areas;
- to develop official plan policies for the implementation of the management strategy into the Grey County Official Plan;
- to ensure that aggregate resources are protected and managed in the County of Grey in a manner that is in the public interest and which has regard for the Provincial Policy Statement.

While the ARMP's goal and purposes extend well beyond the mandate of the ARIP program, the information needed to successfully achieve its aims rests on a regional-scale knowledge and understanding of the quality and quantity of mineral aggregate in the county. Because of these aims, the County of Grey and the Ontario Geological Survey have formed a partnership, the end result of which will be the production of a single ARIP covering the County of Grey and the generation of information required for the completion of the ARMP. The field and office investigations leading to the production of the ARIP are being completed by the consulting firm of Jagger Hims Limited, who are being retained by the County of Grey to work on the ARMP.

PROJECT STATUS

The first phase of work on the new ARIP involves the assembly of geological and mineral aggregate information from various sources. Primary sources of information include, but are not limited to

- aggregate source lists: Ministry of Transportation (MTO);
- surficial and bedrock test results: MTO and pit owners and/or operators;
- water well records: Ministry of Environment;
- pit and quarry license information: Ministry of Natural Resources;
- surficial and bedrock geological maps: Ministry of Northern Development and Mines;
- digital files of existing ARIPs: Ministry of Northern Development and Mines;
- topographic information.

Data assembly and compilation began in the spring of 2002. This phase of the project was sufficiently advanced that field work to collect aggregate-related information, and data to be used in other aspects of the ARMP, commenced in the summer of this year. Information being collected in the field includes

- definition of the deposit outline (i.e., location);
- thickness of the deposits;
- details on the quantity of aggregate (e.g., percentage of fines, deleterious lithologies) in the area's numerous pits and quarries;
- aspects of the local environment and setting that would impact on the development of deposits.

It is expected that the field work will be completed in the fall of 2002. In the course of the field work numerous samples of sand and gravel are being collected. Samples will be submitted to the MTO's Soils and Aggregates laboratory in Downsview and/or private, commercial laboratories where a series of tests will be performed on them. Results of the sample testing will be used to assess aggregate quality on a regional basis.

Following completion of the field work and receiving the test results, the final phase of the project, data synthesis and interpretation, will begin. This phase will see the county's surficial aggregate deposits classified as either primary, secondary or tertiary based on the ARIP program's criteria. Bedrock resources will also be evaluated as to their potential for future development. Selected Resource Areas, indicating areas with high mineral aggregate potential that should be considered for protection in official plans, will be shown on a series of 1:50 000 scale maps covering the county. A discussion on the geology of the area and descriptions of the Selected Resources Areas will be contained in an ARIP that is slated for completion in 2003.

22. Project Unit 01-010. The Quaternary Geology and Sedimentary Architecture of the Longlac Area, Northwestern Ontario

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INTRODUCTION

This project represents the final phase of a multiyear project initiated in the spring of 2001. During the initial phase of this project 247 modern alluvium samples, 92 till samples and 20 sand and gravel samples were collected from the study area (Slattery and Morris 2001). These samples were submitted for heavy mineral analysis to isolate any gold grains, kimberlite indicator minerals (KIMs), metamorphic/magmatic massive sulphide indicator minerals (MMSIM®s), carbonatite indicator minerals and PGE grains. In addition to the regional survey, an orientation survey was completed this year in an effort to validate significant, anomalous KIM values that were identified in 2001. Clast lithologies were determined for the pebbles contained within the bulk alluvium and till samples collected from the orientation survey. This information is essential in determining proximity to source for heavy mineral and geochemical signatures. Information regarding sample collection, sample results and exploration targets pertaining to the Longlac area has been summarized in Morris et al. (2002).

The second and final phase of this project focusses on Quaternary mapping, physiography, geophysical techniques, sedimentary architecture (lithotype assemblage) and landform-sediment relationships. This phase of the project forms the foundation of a mapping-based MSc thesis under an Ontario Geological Survey–Laurentian University Graduate Mapping School Agreement.

From a geological standpoint, the Longlac area is critical in our understanding of the interaction of ponded meltwater between 3 major glacial lake basins: the Lake Nakina, Lake Superior and Lake Ojibway basins. By studying physiography, delineating Quaternary sediments through mapping and deciphering landform–sediment relationships (sedimentary architecture) it is hoped that the constraints on these ice-water and interbasin drainage characteristics can be established in order to construct a viable paleogeographic model for the Longlac area. Included within this report are some of the preliminary findings and the future direction of research regarding the Quaternary geology of the Longlac area.

LOCATION AND ACCESS

The study area lies within the geographic districts of Thunder Bay and Cochrane and is located immediately east of Longlac, Ontario (Figure 22.1). It occupies approximately 2000 km^2, and is bounded by latitudes 86°30′W and 86°00′W and longitudes 50°00′N and 49°30′N. The area includes portions of 12 named geographic townships along with additional, unorganized terrain. The project area is covered by 2, 1:50 000 scale National Topographic System (NTS) map sheets, Castlebar Lake (42 E/16) and Pagwachuan Lake (42 E/9).

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[1] MMSIM is a registered trademark of Overburden Drilling Management Limited, Nepean, Ontario.

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Ontario Geological Survey, Open File Report 6100, p.22-1 to 22-5.

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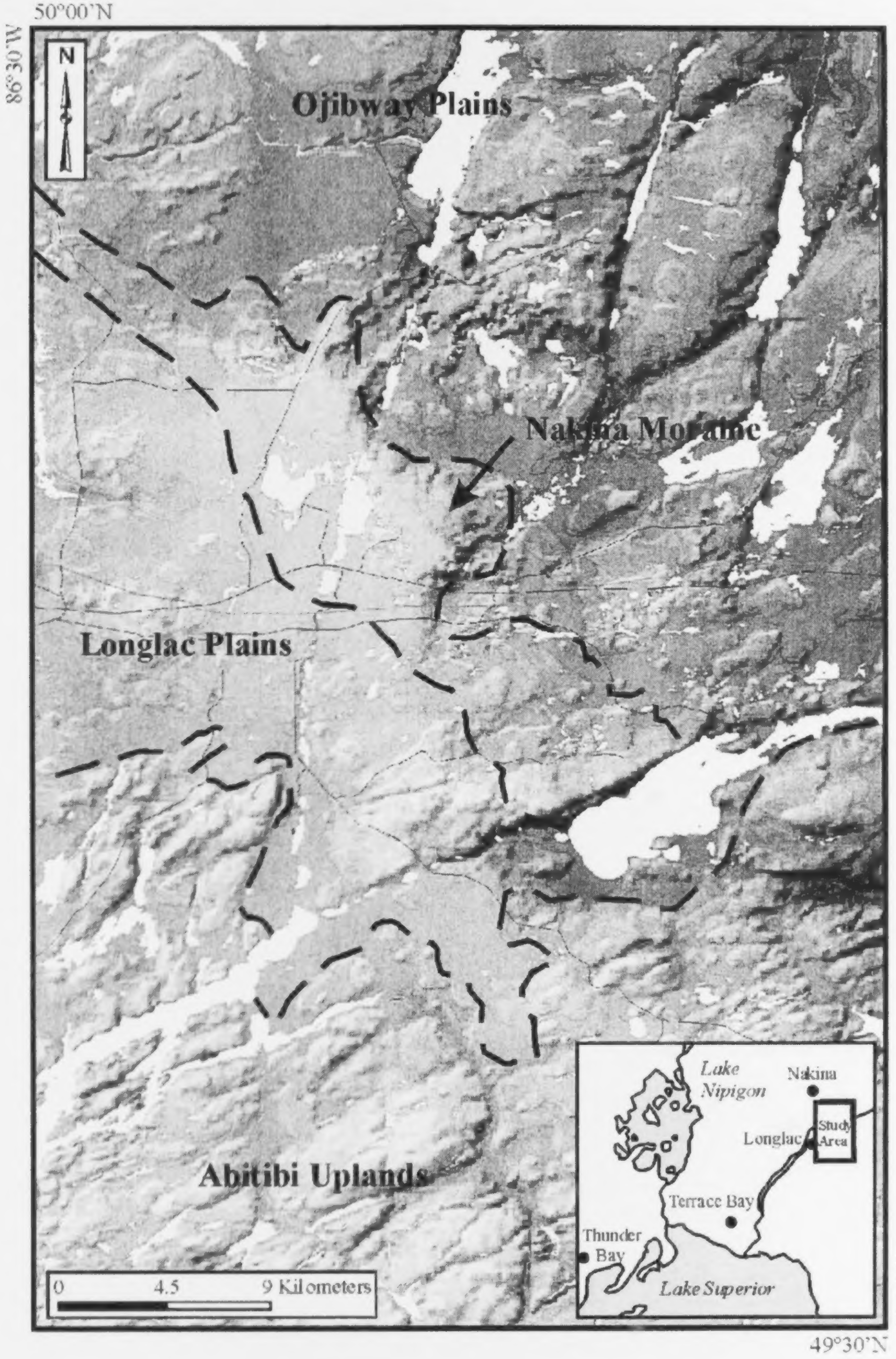
50°00'N
86°30'W
N
Ojibway Plains
Nakina Moraine
Longlac Plains
Abitibi Uplands
0
4.5
9 Kilometers
Lake Nipigon
Nakina
Study Area
Longlac
Terrace Bay
Thunder Bay
Lake Superior
86°00'W
49°30'N

Figure 22.1. A fused product incorporating hill-shade and a digital elevation model (DEM) resulting in the enhancement of local physiographic regions and the study area location.

Road access to the study area is provided by Trans Canada Highway 11, highway 625 and numerous forest access roads. The Canadian National Railway also services the area. The towns of Longlac, Caramat and Local Indian Reserve # 77 are the major population centres within the area. The local economy is based on forestry, the railway, tourism and mineral exploration.

PHYSIOGRAPHY

The study area lies within the Abitibi upland subregion of the James Bay physiographic region (Bostock 1976). This region is underlain by crystalline Archean rocks and characterized by a broad rolling surface that rises gently from the Hudson Bay Lowland. Bedrock relief is generally low to moderate, seldom exceeding 60 m (Gartner 1979).

A fused map product incorporating hill-shade and a digital elevation model (DEM) can be used to visualize the important physiographic regions of the Longlac landscape. On a local scale, the region has been further subdivided by the author into the Longlac plains, the Ojibway plains, the Nakina moraine and the Abitibi upland (*see* Figure 22.1).

BEDROCK GEOLOGY

The Precambrian geology of the Longlac area has been described and mapped in detail by Pye, Harris and Fenwick (1966), Innes and Ayres (1971), Kresz (1989), and Kresz and Zayachivsky (1989). The study area lies within the Wabigoon and Quetico subprovinces of the Superior Province. Within the study area, the eastern Wabigoon Subprovince is, in part, composed of the Elmhirst–Castlewood–Klotz greenstone belt that is of Archean age. This belt trends westerly and is characterized as a chlorite schist surrounded by granitoid units. The greenstone belt consists of massive, pillowed, amygdaloidal, variolitic flows of magnesium to iron tholeiite (Mason and White 1986). The granitoid units are transected by the Nipigon Embayment (Blackburn et al. 1991). Rocks belonging to the Elmhirst–Castlewood–Klotz greenstone belt have been intruded by late intrusive (Neo- to Mesoarchean) diorite, granodiorite, quartz-diorite, monzonite, feldspar porphyry, quartz-porphyry and pegmatite (Mason and White 1986).

The Quetico Subprovince lies to the south of the Wabigoon Subprovince. The Quetico Subprovince consists of Neo to Mesoarchean intrusive and supracrustal rocks composed of a gneissic tonalite suite, muscovite-bearing granite, massive granite to granodiorite and a metasedimentary suite.

Proterozoic diabase dikes intrude all rock types associated with both subprovinces. Metamorphic grade is commonly greenschist facies, but ranges to amphibolite facies (Speed and Craig 1992).

The study area straddles the Trans–Superior Tectonic Zone (TSTZ), a prominent structural feature that extends north-northeast from Michigan where several kimberlites occur. This tectonic zone was emplaced between 1.0 to 1.2 Ga (Sage 1991).

QUATERNARY GEOLOGY

Previous Quaternary mapping for the area has been completed at scales of 1:5 000 000 (Prest, Grant and Rampton 1968), 1:1 000 000 (Barnett, Henry and Babuin 1991), 1:506 880 (Zoltai 1965) and 1:100 000 (Gartner 1979). Specific studies and/or observations on local Quaternary geology features and landforms were reported by Zoltai (1967).

Direction of ice flow within the study area is defined by the orientation of striae, grooves, chattermarks and streamlined bedrock. Most of these features are orientated between 215 and 227°, indicating a regional flow to the southwest. Three tills are present within the study area. The most common till is composed of subglacially derived material with a sandy, carbonate-rich matrix. Clasts from this till have been derived from both local sources and from the Hudson Bay Lowland. A less pervasive, non-calcareous, locally derived till is also present within the study area. This till is confined to the lee side of topographically high areas. A third, clay-rich till, related to the Cochrane readvance (Hughes 1965; Prest 1970) is restricted to areas north of the Nakina moraine.

Landforms and materials associated with ice marginal retreat are found throughout the study area. Ice-contact stratified drift is commonly associated with deltaic sequences, recessional moraine, dead-ice topography, eskers and valley fill. Ice-contact stratified drift consists of poorly to well-sorted, silt to boulder grade material that contains a variety of clast types (from local material to Hudson Bay Lowland derived Paleozoic clasts). The matrix of this material reacts strongly with 10% HCl. Several prominent eskers representing former subglacial conduits supplied sediment to the ice margin where 2 deltas coalesced to form part of the Nakina moraine.

A collaborative venture between Dr. T. Calvert of the Geological Survey of Canada and the Ontario Geological Survey resulted in approximately 21 km of shallow, subsurface ground penetrating radar (GPR) data (using a PulseEKKO IV®[2]) over the Nakina moraine. Additional data, regarding the sedimentary architecture of the moraine were obtained through detailed section logging and mapping of natural and man-made exposures. This detailed work provided 400 m of lateral lithotype assemblage identification. Unprocessed geophysical results and detailed sedimentary architecture indicate that the studied portion of Nakina moraine consists of 2 shallow water, Hjulstrom-type deltas (Hjulstrom 1952).

Glaciofluvial deposits consisting of well-sorted sands to coarse boulders of primarily local provenance were identified within several narrow valleys. Glaciolacustrine deposits located north of the Nakina moraine consist of ryhthmically bedded (varved) very fine sand, silt and clay deposited within glacial Lake Ojibway. Glaciolacustrine sediments located south of the moraine are composed of silty, fine-to medium-textured sands that were deposited in a shallow ice marginal lake. West of Pagwachuan Lake, water from a proglacial lake spilled over the drainage divide into McKay Lake, then drained south to Lake Superior through the Pic River valley.

Postglacial features such as colluvium, modern shoreline features (such as bars and spits), eolian features (sand dunes), modern alluvium and organic deposits were observed throughout the study area.

PROJECT STATUS

Two 1:50 000 scale Quaternary geology maps (NTS map sheets Castlebar Lake, 42 E/16 and Pagwachuan Lake, 42 E/9) and an accompanying Open File Report (OFR) discussing the Quaternary geology, sedimentology and aggregate potential of the Longlac area will be released in the spring of 2003. Quaternary geology maps are useful for a variety of purposes. Amongst other things, they provide information to aid drift prospecting, sand and gravel assessment, the location of environmentally sensitive areas and forest management.

Seven samples consisting of 3 modern alluvium and 4 till were collected in order to verify anomalous KIM values from the previous year (Slattery and Morris 2001). At each till sample site, 250 g samples of each of the humus, "B" and "C" horizons was collected for geochemical analysis. A 10 kg bulk sample of "C" horizon was also collected for heavy mineral analysis. At the modern alluvium sample sites, a 10 kg bulk sample of alluvium was collected for heavy mineral analysis.

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[2] PulseEKKO IV is a registered trademark of Sensors and Software Inc., Mississauga, Ontario.

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23. Project Unit 02-014. Regional Modern Alluvium Sampling Survey of the Cobalt–Elk Lake Area, Northeastern Ontario

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INTRODUCTION

In recent years, the discovery of kimberlite in northeastern Ontario near New Liskeard and Kirkland Lake has triggered an increase in diamond exploration across the region. In these areas, the thickness of glacial sediments ranges from nil to greater than 100 m. Kimberlite, being relatively soft, has been differentially eroded by preglacial weathering and glacial erosion such that it subcrops 3 to 35 m below the surrounding bedrock (McClenaghan et al. 1999a). Because of this deep erosion, all kimberlite pipes in the area are covered by glacial sediments and have no surface expression. Through indicator mineral and geophysical surveys, several kimberlite pipes and dikes have been discovered in the region within the last 15 years (McClenaghan et al. 1999b).

To further evaluate the diamond and other mineral potential of this region of northeastern Ontario, the Ontario Geological Survey completed a modern alluvium survey in the Temagami–Marten River area during the summer of 2000 (Allen 2001) and another along the Mattawa–Cobalt corridor during the summer of 2001 (Figure 23.1) (Reid 2002). The current study, covering the Cobalt–Elk Lake area is an extension of the survey completed in 2001 (Figures 23.1 and 23.2). The primary objective of the current study is to extend the regional information base concerning the types and distribution of kimberlite indicator minerals (KIMs) found in modern alluvium northwestward to the Elk Lake area.

Exploration for kimberlite indicator minerals remains very active throughout northeastern Ontario. Over 22 000 new claim units have been recorded within the Temagami–Marten River survey area following the release of the Temagami–Marten River indicator mineral report in April 2001. Since the release of the Mattawa–Cobalt corridor indicator mineral report in June 2002, almost 3000 new claim units have been recorded in that area alone (V. Felix, OGS, personal communication, 2002).

Kimberlite is a rock type commonly recognized as the primary host for diamond. The suite of kimberlite indicator minerals is known to include pyrope and eclogitic garnets, magnesium ilmenite, chromite, chrome diopside, forsteritic olivine and diamond. The presence of these indicator minerals in collected samples will be used to determine the prospect for and proximity of any diamond-bearing kimberlite in the area. As well, heavy mineral assemblages will be examined for gold grains and metamorphic or magmatic massive sulphide indicator minerals (MMSIM®s [1])

The Cobalt–Elk Lake study area is represented on 10, 1:50 000 scale National Topographic System (NTS) map sheets. The northwest part of the study area is covered by the southwest corner of the Charlton sheet (41 P/16), the east half of the Gowganda sheet (41P/10), the southeast corner of the

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[1] MMSIM is a registered trademark of Overburden Drilling Management Limited, Nepean, Ontario.

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Matachewan sheet (41P/15), the north corner of the Smoothwater Lake sheet (41 P/7) and the entire Elk Lake sheet (41 P/10). The southeast part of the study area is covered by the west half of the Cobalt sheet (31 M/5), the east half of the Lady Evelyn Lake sheet (41 P/8), the northeast corner of the Obabika Lake sheet (41 P/1), the northwest corner of the Temagami sheet (31 M/4) and the southwest corner of the New Liskeard sheet (31 M/12).

A network of primary and secondary roads and all-terrain vehicle (ATV) trails provided reasonable access to the study area. The presence of numerous lakes and rivers provided boat access to otherwise remote locations. The larger lakes allowed for float plane access and very remote sites were accessed by helicopter.

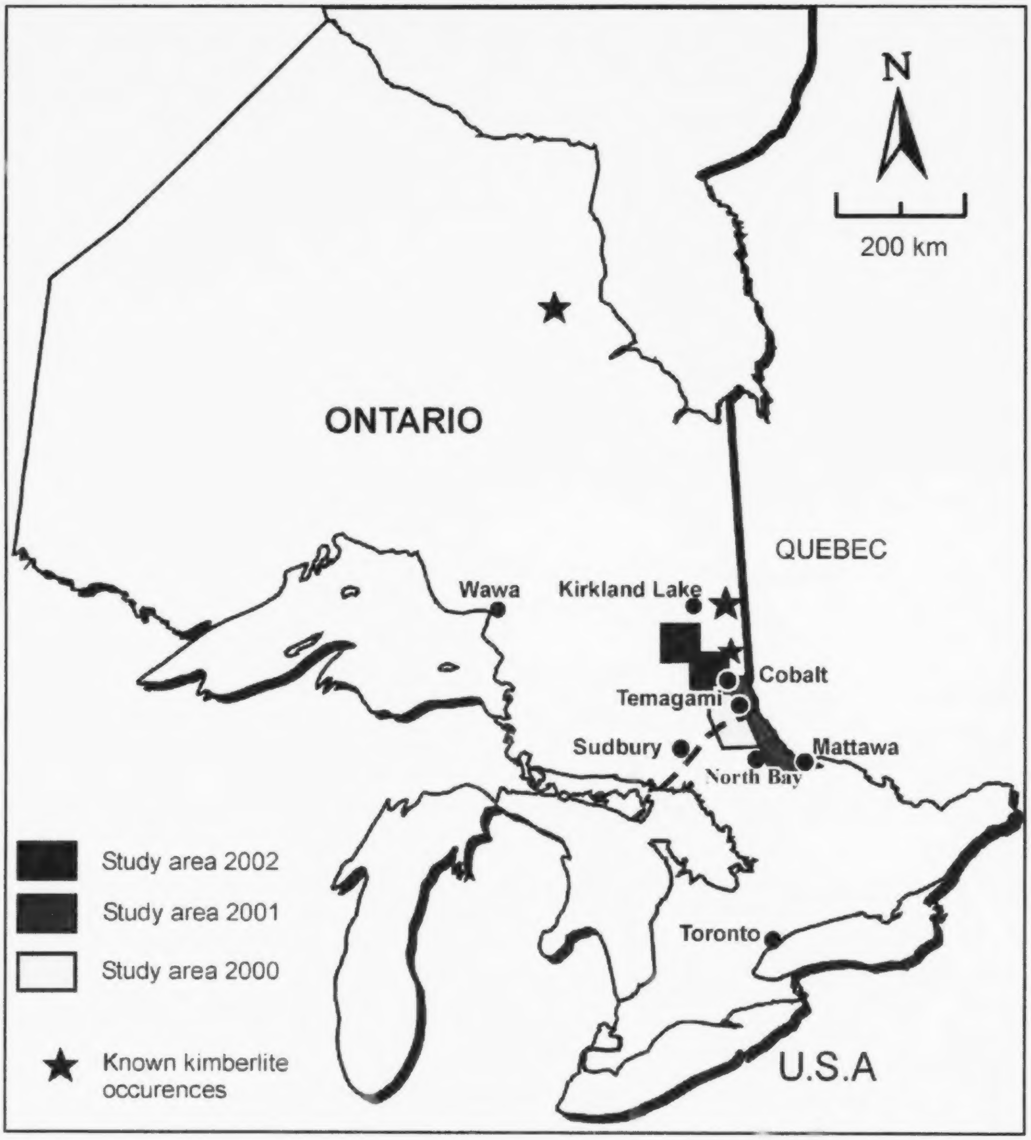
N
200 km
ONTARIO
QUEBEC
Wawa
Kirkland Lake
Cobalt
Temagami
Sudbury
Mattawa
North Bay
Toronto
U.S.A
Study area 2002
Study area 2001
Study area 2000
Known kimberlite occurences

Figure 23.1. Location of the 2002 study area in relation to the 2000 and 2001 study areas. Locations of known kimberlites *from* Sage (1996).

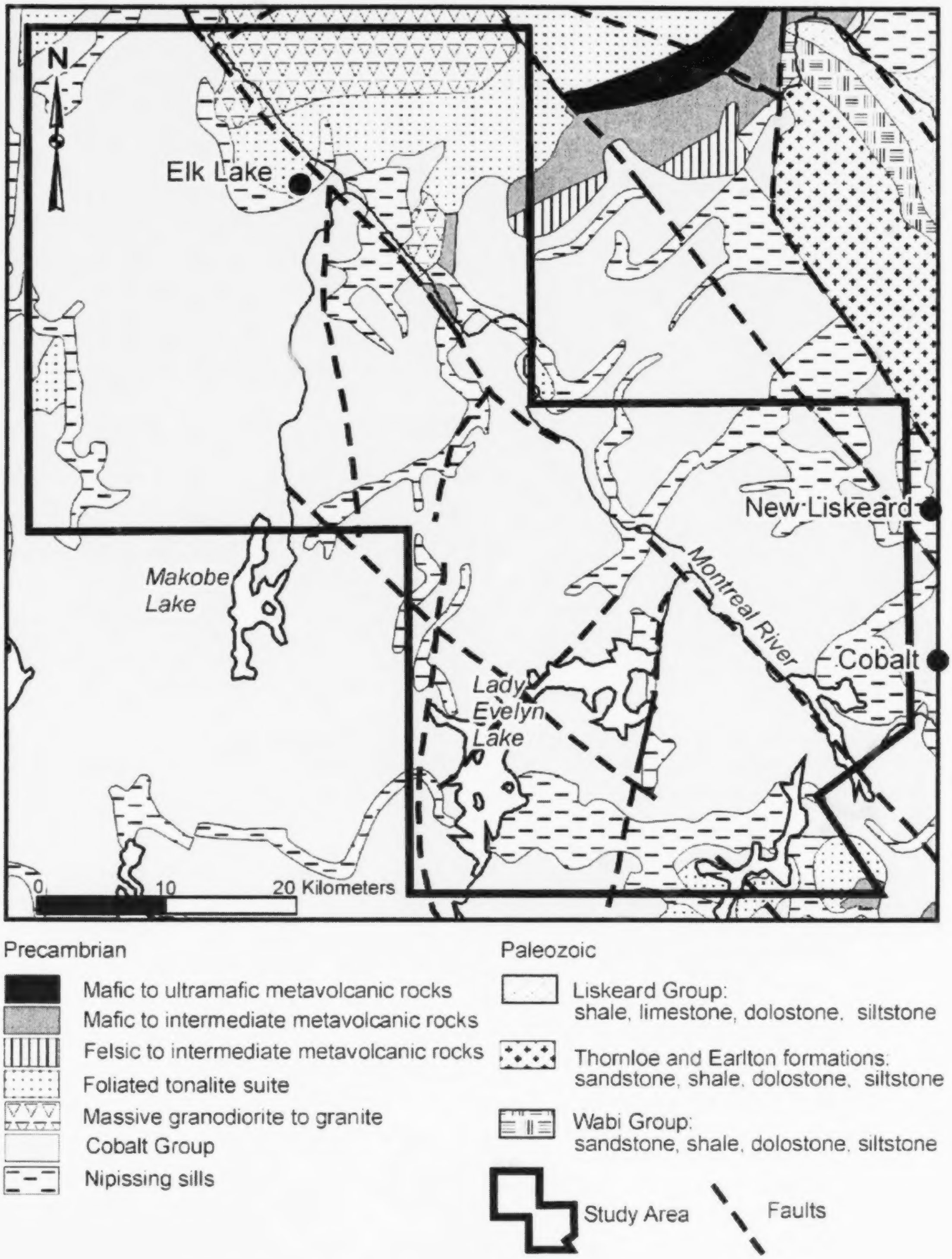
N
Elk Lake
Makobe Lake
Lady Evelyn Lake
New Liskeard
Montreal River
Cobalt
0 10 20 Kilometers
Precambrian
Mafic to ultramafic metavolcanic rocks
Mafic to intermediate metavolcanic rocks
Felsic to intermediate metavolcanic rocks
Foliated tonalite suite
Massive granodiorite to granite
Cobalt Group
Nipissing sills
Paleozoic
Liskeard Group: shale, limestone, dolostone, siltstone
Thornloe and Earlton formations: sandstone, shale, dolostone, siltstone
Wabi Group: sandstone, shale, dolostone, siltstone
Study Area
Faults

Figure 23.2. Location and general bedrock geology of the study area (*after* Ontario Geological Survey 1991).

PHYSIOGRAPHY

The study area is situated in a physiographic division of the Canadian Shield known as the "Cobalt Plain" (Bostock 1976). In general, the low hummocky terrain of the Cobalt plain is controlled by flat-lying sedimentary Precambrian bedrock (Thurston 1991).

The area surrounding the town of Elk Lake can be subdivided, on the basis of relative relief, into clayey and sandy lowlands interrupted by rocky uplands. Sandy plains pass gradually into rocky uplands to the north and east (Roed 1979a). Elevation in this area ranges from 360 to 425 m asl, with some hills reaching 460 m asl. The northwestern part of the study area is of relatively low relief and characterized by numerous bedrock outcrops and widespread sand plains. Elevations range from about 240 to 365 m asl. Most uplands are marked by prominent patterns of north-trending narrow valleys that are controlled by faults such as the Montreal River fault system (Roed 1979a). Drainage in this area is essentially controlled by bedrock structure. The southeasterly trending streams occupy prominent lineaments that strike roughly parallel to the Montreal River (MacKean 1968). As well, several streams are aligned in a northerly direction and are possibly fault controlled, as indicated by the Makobe River (MacKean 1968).

The New Liskeard lowland characterizes the southeast portion of the study area near New Liskeard. This lowland lies within a major fault-controlled rift valley (Roed 1979b). Much of the area is nearly flat and underlain by glaciolacustrine clay-rich beds that were deposited in glacial lake Barlow–Ojibway. The area is commonly known as the "Little Clay Belt". Elevations range from 180 to 360 m asl (Roed 1979b). The main drainage system in this area comprises Wabi Creek and its tributaries. Wabi Creek drains southeastward along the strike of the lowest rift valley fault block and empties into Lake Timiskaming. Lake Timiskaming occupies a fault-controlled valley and is the largest lake in the area (Roed 1979b).

The western half of the southern part of the study area is dominated by rugged dissected uplands of the Cobalt plain (Roed 1979c). Some hills in this area reach elevations as high as 701 m asl. Large lakes in the area, such as Lady Evelyn and Anima Nipissing, drain to the north via small creeks into the Montreal River, which in turn flows into the Lake Timiskaming–Ottawa River system.

BEDROCK GEOLOGY

The oldest rocks in the study area are Neo- to Mesoarchean (2.5 to 3.4 Ga) age and belong to the Abitibi Subprovince of the Superior Province. Located in the northeast corner of the survey area, rock units include granitic rocks of the Round Lake batholith, mafic to intermediate metavolcanic rocks and intrusive massive granodiorite and foliated tonalite suite rocks (Ontario Geological Survey 1991).

Most of the area surveyed is composed of lithologic units of the Southern Province and specifically the Paleoproterozoic Huronian Supergroup (2200 to 2450 Ga) (Ontario Geological Survey 1991). This supergroup is subdivided into 4 groups, one of which, the Cobalt Group or the uppermost sedimentary cycle, is found in the study area. The Cobalt Group comprises, in ascending order, 4 formations: the Gowganda, Lorrain, Gordon Lake and Bar River formations (Bennett, Dressler and Robertson 1991). Of interest to the present study are the Gowganda and Lorrain formations that make up the Cobalt Embayment. The Gowganda Formation consists of 2 members, the Coleman and Firstbrook. The Coleman Member is composed of pebbly wacke, argillite, conglomerate and quartzite (Lovell and Frey 1976). The Firstbrook Member comprises argillite, siltstone, mudstone and metamorphosed sediments and conformably overlies the Coleman Member. The Lorrain Formation consists of arkose, quartzite, mudstone and contact metamorphic rocks (Born and Burbidge 1997) and conformably overlies the Gowganda Formation.

Intruding the Huronian Supergroup are Paleoproterozoic swarms of Nipissing Diabase dikes and sills (2219 Ma). Such rocks consist of diabase, gabbro, quartz gabbro, quartz diabase, varied texture diabase and granophyre (Johns 1985). As well, a series of Mesoproterozoic (0.9 to 1.6 Ga) northwest-trending coarse- and fine-grained olivine diabase dikes known as the Sudbury swarm are found locally in the area (Ontario Geological Survey 1991).

Faults and joints in the bedrock are numerous and the presence of many faults is evident in the terrain. Parallel, northwest-trending fault systems are the most prominent ones in the study area and include the Cross Lake and Montreal River faults (Roed 1979c).

QUATERNARY GEOLOGY

During the Wisconsin Episode, the study area was covered by glacial ice of the Laurentide Ice Sheet (Roed 1979a). In general, glacial ice advanced south to southwestward across the study area (Barnett 1992). On the basis of glacial striae orientations in the Timiskaming area, it has been proposed that 3 different stages of ice flow direction affected the region (Veillette 1986). The oldest, a west-southwest flow (230 to 270°) and a younger, south-southwest flow (180 to 220°) were overprinted by the latest regional south-southeast ice flow (130 to 170°) (Veillette 1986). For the most part, one set of striae were observed during the course of the present study. Striae ranged from 180 to 210° and are thought to be related to the widespread south-southwest flow noted by Veillette (1986). Locally, in the Elk Lake area, 2 sets of striae were observed. An older set ranging from 205 to 210° was crosscut by a younger set of striae measuring approximately 195°.

Glacial deposits present in the Elk Lake–New Liskeard region are thought to be primarily of Late Wisconsinan age (Roed 1979a). Advance of the Laurentide Ice Sheet across the area deposited a discontinuous cover of silty sand till (McClenaghan et al. 1999a). By approximately 10 000 years ago, the glacial front had receded to the current area of study. Extensive esker and deltaic complexes, kames and kettles and the hummocky moraine north of Lady Evelyn Lake were deposited and represent a major stillstand of this ice sheet (Roed 1979c). All of the eskers in the area are composed essentially of sand, gravel, pebbles and some cobbles (MacKean 1968).

Approximately 9500 years ago, the ice front had receded well to the north of the map area. At that time, glacial Lake Barlow joined with glacial Lake Ojibway to form glacial Lake Barlow–Ojibway. Meltwater from the Elk Lake valley emptied into this lake along the western part of the New Liskeard lowland (Roed 1979a). Approximately 8700 years ago, the obstructions along the Lake Timiskaming valley were breached and glacial Lake Barlow–Ojibway drained in several stages eventually resulting in modern Lake Timiskaming (Roed 1979b). Thick deposits of fine-grained glaciolacustrine sediments associated with glacial Lake Barlow–Ojibway are found within the eastern part of the study area.

Other deposits associated with retreat of the ice front from the area include 1) glaciolacustrine deposits of sand and gravel, nearshore and beach deposits; 2) glaciofluvial outwash deposits of gravel and sand; and 3) localized fluvial deposits of gravel, sand, silt and clay (Barnett, Henry and Babuin 1991).

Recent deposits consist mainly of organic swamp deposits and lake sediments and are found throughout the survey area (Born and Burbidge 1997).

REGIONAL SAMPLING SURVEY

The current regional modern alluvium survey, covering a total area of approximately 2850 km^2, was conducted in July and August 2002. A total of 175 modern alluvium samples, 2 till and 6 glaciofluvial sand and gravel samples were collected. Access to sample locations was achieved by truck, ATV, boat, float plane and helicopter. The resulting distribution of collected samples provides excellent regional coverage. Regional overburden heavy mineral surveys provide data on the types, distribution and relative concentration of heavy minerals in a given region. The number of samples collected was predetermined by budget and time considerations, however, samples were collected over as broad an area as possible. The position of each sample was accurately recorded with a geographic positioning system (GPS) instrument set to North American Datum (NAD) 83 and using NTS 1:50 000 scale map sheets situated in UTM zone 17.

Modern alluvium was chosen as the primary sampling media for this study as it provides a means of obtaining a fast, relatively inexpensive heavy mineral signature for individual drainage basins (Morris et al. 2000). Points of heavy mineral deposition within streams were targeted for sample collection. Sampling points included the deepest part of the channel; longitudinal and point bars; and boulder, log and vegetation traps (Morris et al. 2000). Material was sieved in the field using a 5 mm mesh screen and the finer fraction (<5 mm) was retained. Sample weight ranged from 10 to 20 kg. At some sites, larger samples were collected to compensate for either a high percentage of fine-sand or silt material in the sediment or the dilution of heavy mineral grains caused by a high percentage of organic material. The fraction of the sample smaller than 5 mm was sent for heavy mineral processing to separate possible kimberlite and other indicator minerals. Where possible, approximately 50 pebbles were collected from the coarser (>5 mm) fraction at each sample site for pebble lithology classification. Pebble lithologies classified to date indicate that, typically, stream deposits are locally derived. In addition, at each site, a small portion of the stream sediment was panned and the resultant "fine-fraction" concentrate retained.

At each sample location, a site description consisting of observations on: 1) genesis of material, stream flow and depth; 2) surface expression; 3) slope inclination and aspect; 4) drainage; 5) vegetation type and state; 6) glacial features; 7) anthropogenic factors; 8) material description consisting of a) texture; b) structure; c) bar form, d) clast size, abundance, shape and type; and 9) diagrams and additional comments, was completed. Photographs were taken at several sites.

Results from the study are expected to be released in the spring of 2003.

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24. Project Unit 00-033. Method Development for the Generation of Engineering Terrain Maps in Ontario's Far North

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[2]Canada Centre for Remote Sensing, Natural Resources Canada, Ottawa

INTRODUCTION

The Ontario Geological Survey and Canada Centre for Remote Sensing have undertaken a project to develop a methodology for engineering geology terrain analysis using Digital Elevation Models (DEMs) and remotely sensed imagery for remote areas within the boreal forest region of the Canadian Shield. Four main components of the terrain are considered: material, landform, relief and regional drainage conditions; this follows the existing format of Northern Ontario Engineering Geology Terrain Studies (NOEGTS) maps (Gartner, Mollard and Roed 1981). NOEGTS maps provide useful information concerning the landscape for forest management, mineral exploration and civil engineering undertakings.

The NOEGTS map legend contains information on surface material type, landform, topography (relief) and drainage condition. The maps were perhaps ahead of their time, attempting to show 4 landscape properties on 1 paper map; commonly requiring the use of complex legend codes. With the advent of Geographical Information Systems (GIS), it is easy to display the legend components as 4 individual layers without the loss of detail that necessarily occurs when combining them into 1 layer. Over the past few years, methods for creating or predicting landform, topography (relief) and drainage condition components of the NOEGTS legend have been developed and work is continuing on defining material type (Barnett and Singhroy 2000, 2001; Singhroy et al. 2000).

PROGRESS TO DATE

Landform (roughness) and relief can be derived automatically from an analysis of a detailed hydrological-conditioned DEM. For roughness, a nearest-neighbourhood analysis of the variety of elevation is performed on an integer version of the DEM. The results are grouped into 3 classes: 2 types of plains with relief averaging 1 m, and 3 m, respectively, and rough areas with relief greater than 5 m. The rough areas are further subdivided following an analysis of the variety of aspect and application of a majority filter. This enables the rough areas to be divided into areas of escarpments (low variety of aspect) and areas of irregular terrain (high variety of aspect), thus producing 4 roughness classes. The spatial distribution of the various roughness-relief polygons assists in defining landforms, such as a ridge, terrace, etc. Further work into distinguishing landform type is proceeding following a method modified from Digital Elevation Model Terrain Analysis Tool (DEMTAT) developed by S. Leney (S. Leney, Ministry of Natural Resources, Peterborough, personal communication, 2002).

Relief is derived from the DEM using a nearest-neighbourhood analysis of the range of elevation. The circular neighbourhood used has a radius greater than half the width of the largest landforms in the

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area studied. The results are classified into 6 classes and then the radius of the neighbourhood used internally buffers each class. They are then added sequentially and clipped by the roughness polygons. The plains from the roughness process are assigned relief values of less than 5 m and the rough area polygons are subdivided into polygons with the classified values of relief. Two relief layers have been produced for each map sheet; one layer with the same relief divisions as the NOEGTS maps (<15 m, 15 to 60 m and >60 m) and a map with 15 m intervals of relief.

In addition to relief and roughness layers, layers of slope and aspect have been derived and classified from the DEM. Slope is grouped into 5 classes (<1°, 1 to <2°, 2 to <5°, 5 to <12° and >12°) and aspect 4 classes (northeast, southeast, southwest and northwest).

Regional drainage conditions are estimated from RADARSAT imagery. A mask, based on aspect and slope, is created to limit the effects of topography and viewing geometry on backscatter. The imagery is classified into 6 classes for use in prediction of material type, but classed into 3 classes (wet, mixed and dry) to reproduce NOEGTS legend information.

Various types of analysis of Landsat imagery are then combined with all the above digital data layers to interpret and/or predict material type. A series of Satellite Image Maps, a fused product of enhanced Landsat infrared bands 4, 5 and 7 and hillshaded DEM, are being prepared for the 47, 1:100 000-scaled tiles of the study area. These Image Maps are useful for orienting and planning various types of ground survey operations and aid in the interpretation of landforms and material types. Landcover derived from the Landsat imagery has also been found to be useful for material identification. Principal component analysis of the imagery shows promise but has not been fully evaluated.

Several methods of material prediction are being evaluated. One is a totally automated method that first determines the relationships of the various layers of digital information described above in areas of known terrain conditions, then predicts terrain conditions in adjacent unmapped areas. The Red Lake area (Prest 1963) and the North Caribou Lake area (Finamore 1986, Finamore and Carswell 1986a, 1986b) that were previously mapped at a scale of 1:50 000, are being used as the known terrain conditions. Probability maps for each material type are produced during this method. Figure 24.1 provides an example of a prediction for sand and gravel in the Windigo Lake area. The second method being evaluated considers the percentage of the predicted material types that occur within each roughness polygon and assigns that material to the polygon. The third method to be evaluated will have more user involvement in the material designation. All layers of data will be examined and the most likely material chosen will be based on geological experience.

Data sets of slope, aspect, roughness and relief in addition to the Satellite Image Maps have been created for the entire study area. Regional moisture conditions have been defined for the test sites and work continues on material prediction methodologies. The derived information can be used for regional planning purposes in drift exploration, forest management and in ecological land classification studies by both private and public organizations. In mineral exploration, it can be used in planning for field operations: providing information on terrain and forest conditions and in determining techniques and locations for sampling. The interpretation of sample results (depositional environment, direction of ice flow) may also benefit from the information collected during this project. One example of an applied study using the data collected during this project is a preliminary volume analysis of the mineral aggregate resources for selected parts of northwestern Ontario requested by the Ontario Ministry of Transportation.

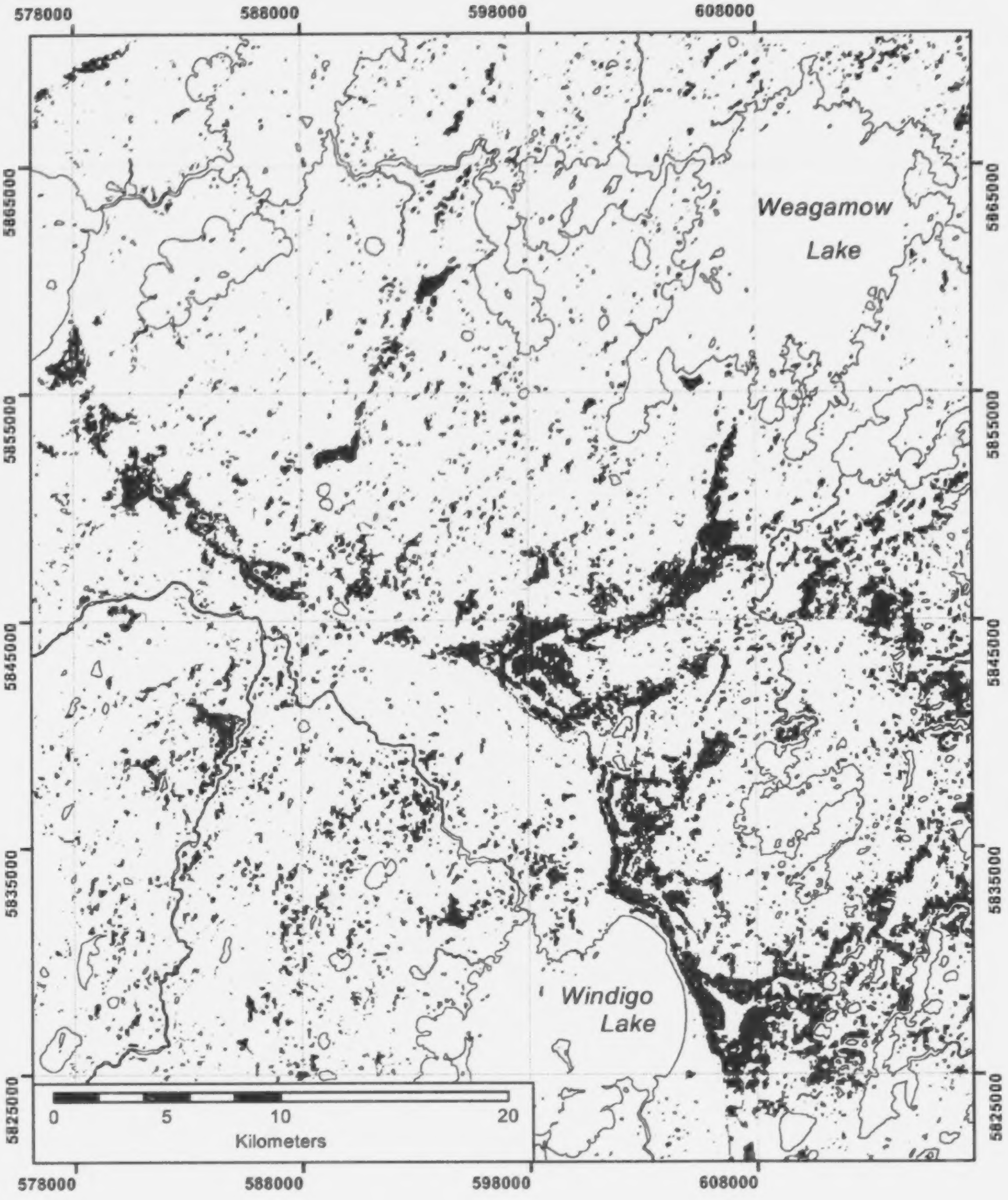
578000
588000
598000
608000
5865000
5855000
5845000
5835000
5825000
Weagamow Lake
Windigo Lake
0
5
10
20
Kilometers

Figure 24.1. An example of an automated prediction for sand and gravel in the Windigo Lake area. Areas of potential sand and gravel occur in black and correspond nicely to landforms such as the Aqutua moraine and several southwest-trending eskers.

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25. Project Unit 02-012. Biscotasi Lake Area High Density Regional Lake Sediment and Water Geochemical Survey, Northeastern Ontario

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INTRODUCTION

A helicopter-supported regional lake sediment and water geochemical survey of the Biscotasi Lake area was conducted by staff of the Ontario Geological Survey (OGS) from July 15 to July 30, 2002. Biscotasi Lake is located approximately 120 km northwest of Sudbury, Ontario (Figure 25.1). The survey area covered the southeastern and southern extensions of the Swayze greenstone belt near Gogama and Lake Biscotasi, respectively (Figure 25.2). The Swayze greenstone belt is the westward extension of the Abitibi greenstone belt and encompasses an area of about 8000 km^2. Lake and water samples were collected from a 2713 km^2 region that encompasses portions of the area represented on National Topographic System (NTS) map sheets 41 O/1, 41 O/8, 41 O/9, 41 P/4, 41 P/5 and 41 P/12. Lake sediment and/or water samples were collected at 1051 sites for an average density of 1 sample per 2.5 km^2. This lake water and sediment survey forms the first part of a three-year project to collect geochemical samples from the Swayze greenstone belt. The Swayze greenstone belt was selected for this type of geochemical survey because of its high potential for base and precious metal mineralization and because lake sediment and water geochemistry is an effective and expeditious method to assess the regional mineral potential of an area.

BEDROCK GEOLOGY

The Swayze greenstone belt (SGB) is located in the western Abitibi Subprovince of the Superior Province. The Swayze greenstone belt is bounded on the north by the Nat River granitoid complex, on the west by the Kapuskasing structural zone, on the south by the Ramsey–Algoma granitoid complex and on the east by the Kenogamissi granitoid complex. The SGB is connected to the Abitibi greenstone belt by a narrow band of metasedimentary and metavolcanic rocks that wrap around the northern and southern margins of the Kenogamissi granitoid complex (Jackson and Fyon 1991).

Massive peridotite, pyroxenite and dunite intrusions are common within the SGB. These ultramafic rocks are also spatially related to polysutured and spinifex textured komatiite volcanic flows (Heather 2001). Mafic to intermediate metavolcanic and synvolcanic intrusive rocks are widely dispersed throughout the belt. These include iron-tholeiitic basalt, magnesium-tholeiitic basalt, calc-alkalic basalt, and gabbro and/or diorite sills and dikes. The metavolcanic rocks consist of massive, pillowed, pillow breccia, variolitic and amygdaloidal flows. Several large sequences of felsic to intermediate metavolcanic rocks also occur within the SGB and consist of massive to pillowed flows and associated pyroclastic rocks. Chemical metasedimentary rocks consisting of sulphide- and carbonate-facies iron formations occur within most of the metavolcanic sequences within the SGB. Older sequences of clastic metasedimentary rocks in the SGB contain a close temporal and tectonic relationship to the metavolcanic

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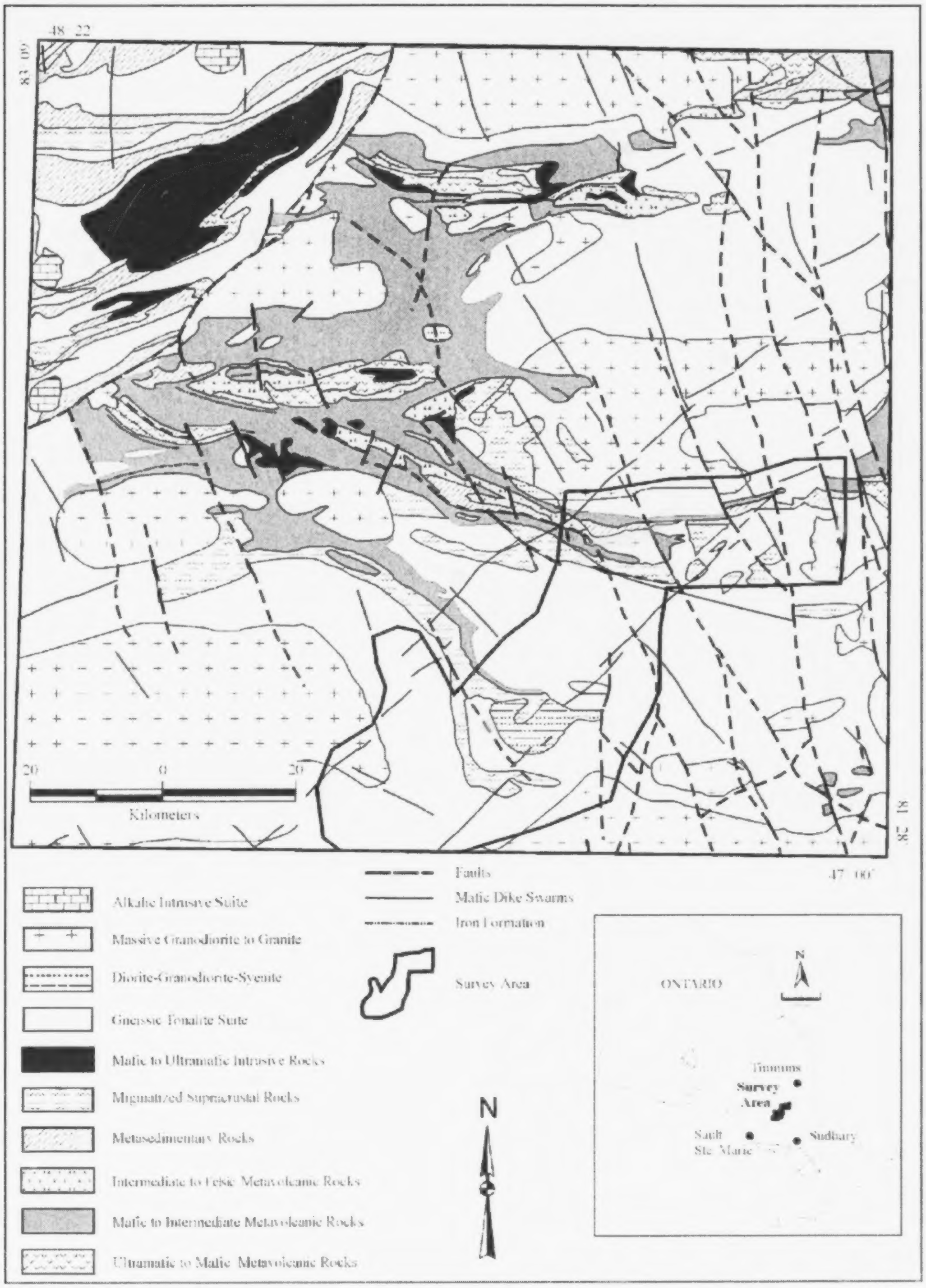
48°22'
83°09'
81°28'
47°00'
20
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Kilometers
Alkalic Intrusive Suite
Massive Granodiorite to Granite
Diorite-Granodiorite-Syenite
Gneissic Tonalite Suite
Mafic to Ultramafic Intrusive Rocks
Migmatized Supracrustal Rocks
Metasedimentary Rocks
Intermediate to Felsic Metavolcanic Rocks
Mafic to Intermediate Metavolcanic Rocks
Ultramafic to Mafic Metavolcanic Rocks
Faults
Mafic Dike Swarms
Iron Formation
Survey Area
N
ONTARIO
N
Timmins
Survey Area
Sault Ste. Marie
Sudbury

Figure 25.1. Location map of the Biscotasi Lake area lake sediment and water geochemical survey. Bedrock geology *after* Ontario Geological Survey (1991).

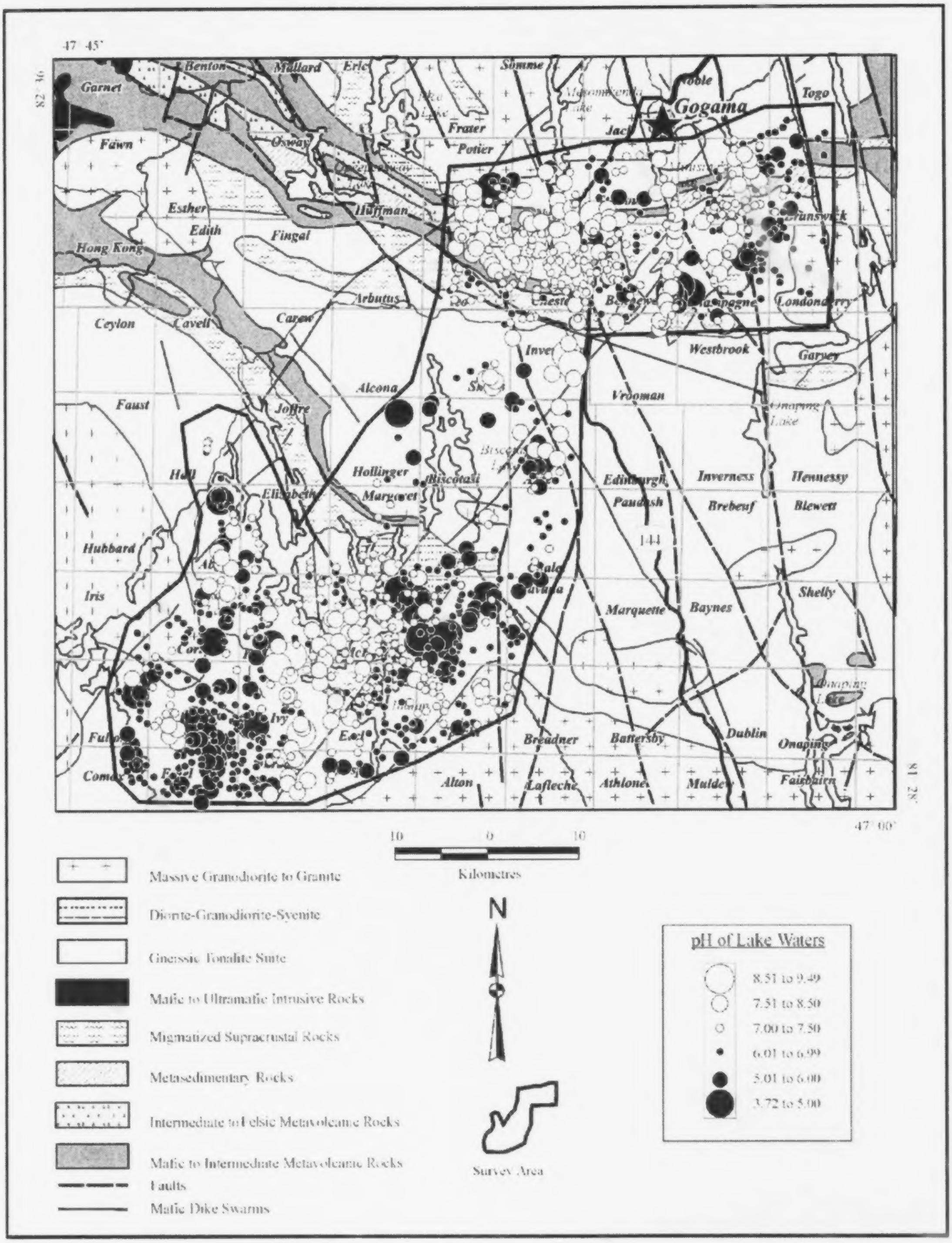
47°45'
82°36'
81°28'
47°00'
Garnet
Benton
Mallard
Erle
Somme
Noble
Gogama
Togo
Fawn
Osway
Frater
Potier
Esther
Edith
Fingal
Huffman
Brunswick
Hong Kong
Arbutus
Londonderry
Ceylon
Cavell
Carew
Westbrook
Garvey
Alcona
Vrooman
Faust
Joffre
Hall
Hollinger
Biscotasi
Margaret
Elizabeth
Edinburgh
Paudash
Inverness
Brebeuf
Hennessy
Blewett
Hubbard
Iris
Marquette
Baynes
Shelly
Dublin
Onaping
Alton
Lafleche
Athlone
Mulder
Fairbairn
Onaping Lake
10
0
10
Kilometres
N
Survey Area
Massive Granodiorite to Granite
Diorite-Granodiorite-Syenite
Gneissic Tonalite Suite
Mafic to Ultramafic Intrusive Rocks
Migmatized Supracrustal Rocks
Metasedimentary Rocks
Intermediate to Felsic Metavolcanic Rocks
Mafic to Intermediate Metavolcanic Rocks
Faults
Mafic Dike Swarms
pH of Lake Waters
8.51 to 9.49
7.51 to 8.50
7.00 to 7.50
6.01 to 6.99
5.01 to 6.00
3.72 to 5.00

Figure 25.2. Generalized bedrock geology and pH in lake waters of the Biscotasi Lake survey area. Bedrock geology *after* Ontario Geological Survey (1991).

rocks in the belt (Heather 1993). Younger sequences of clastic metasedimentary rocks in the SGB unconformably overlie the older supracrustal sequences and are likely correlative with the Timiskaming assemblage rocks in the Abitibi greenstone belt (Jackson and Fyon 1991). The present geochemical survey covered the metavolcanic and metasedimentary rocks extending into the Gogama and Biscotasi Lake areas (*see* Figure 25.2). The SGB has a high potential for mesothermal gold, volcanogenic massive sulphide copper-zinc-lead and mafic to ultramafic intrusive and extrusive related nickel-copper ± platinum group element (Ni-Cu ± PGE) mineralization (Heather 1993).

PHYSIOGRAPHY AND QUATERNARY GEOLOGY

Low to moderate relief typifies most of the terrain in the Gogama and Biscotasi Lake areas. Low relief is typical over glaciofluvial and eolian deposits and moderate relief is prevalent in morainal and bedrock-dominated terrain. Steep-sided gullies form along north- and northwest-trending regional fault zones. Elevations in the area range from 340 to 550 m asl.

A regional compilation of the Quaternary geology (Barnett, Henry and Babuin 1991) indicates that most of the bedrock in the study area is covered by a thin veneer of discontinuous drift (Figure 25.3). The most significant Quaternary deposit in the area is a morainal scarp (the Sultan Scarp) located approximately 20 km south of Gogama, Ontario (Roed and Hallett 1979). The Sultan Scarp may have formed during a halt in the recession of the Keewatin lobe of the Laurentide ice sheet approximately 11 000 years ago (Roed and Hallett 1979). The scarp is bounded on the south by an extensive glaciofluvial outwash plain. Several esker complexes are also located in the Gogama area. The eskers occur as southward trending ridges of sand and gravel flanked by gently rolling outwash plains (Roed and Hallett 1979).

SAMPLING METHODS

Where possible, organic lake sediment and water samples were collected at each lake site by two-person teams using a float-equipped helicopter. If a site contained no organic component (e.g., sand and/or clay), then, only a water sample was taken. The organic sediment was collected in a gravity corer that was lowered from the helicopter float and then pulled to surface. Collected sediment was then deposited into a sample bag. The upper 20 cm of the sample core was discarded to avoid anthropogenic bias in the geochemical data and to avoid water/sediment interface effects (i.e., increased manganese due to anoxic conditions that result in secondary accumulation of base metals). The sediment below the 20 cm depth better reflects the natural element abundance that may be attributed to the local geology. Each sample was then sealed in an airtight plastic bag in order to avoid contamination between samples.

Lake water samples were collected at a depth of 0.5 m, below surface, from shallow lakes (<3 m deep) and at a depth of 2 m from deep lakes (>3 m). A semi-automated water sampling apparatus, developed by the OGS, was utilized for water collection. The apparatus consists of a submersible pump, a flow cell (for measurement of parameters such as pH, conductivity, oxidation-reduction potential and dissolved oxygen), a sample bottle tray and various hoses and pinch valves. Water is pumped from the lake and allowed to purge the sampling system prior to collection of a water sample and the recording of water quality parameters. Water samples were kept cool after collection and processed (filtered and acidified) within 24 hours of collection.

At each site, sediment descriptions and observations were recorded on standardized forms and entered into a computer database at the end of each day. The pH, temperature, conductivity, oxidation-reduction potential and dissolved oxygen of the water samples was recorded on a water-quality analyzer and a GPS waypoint for the sample sites was taken.

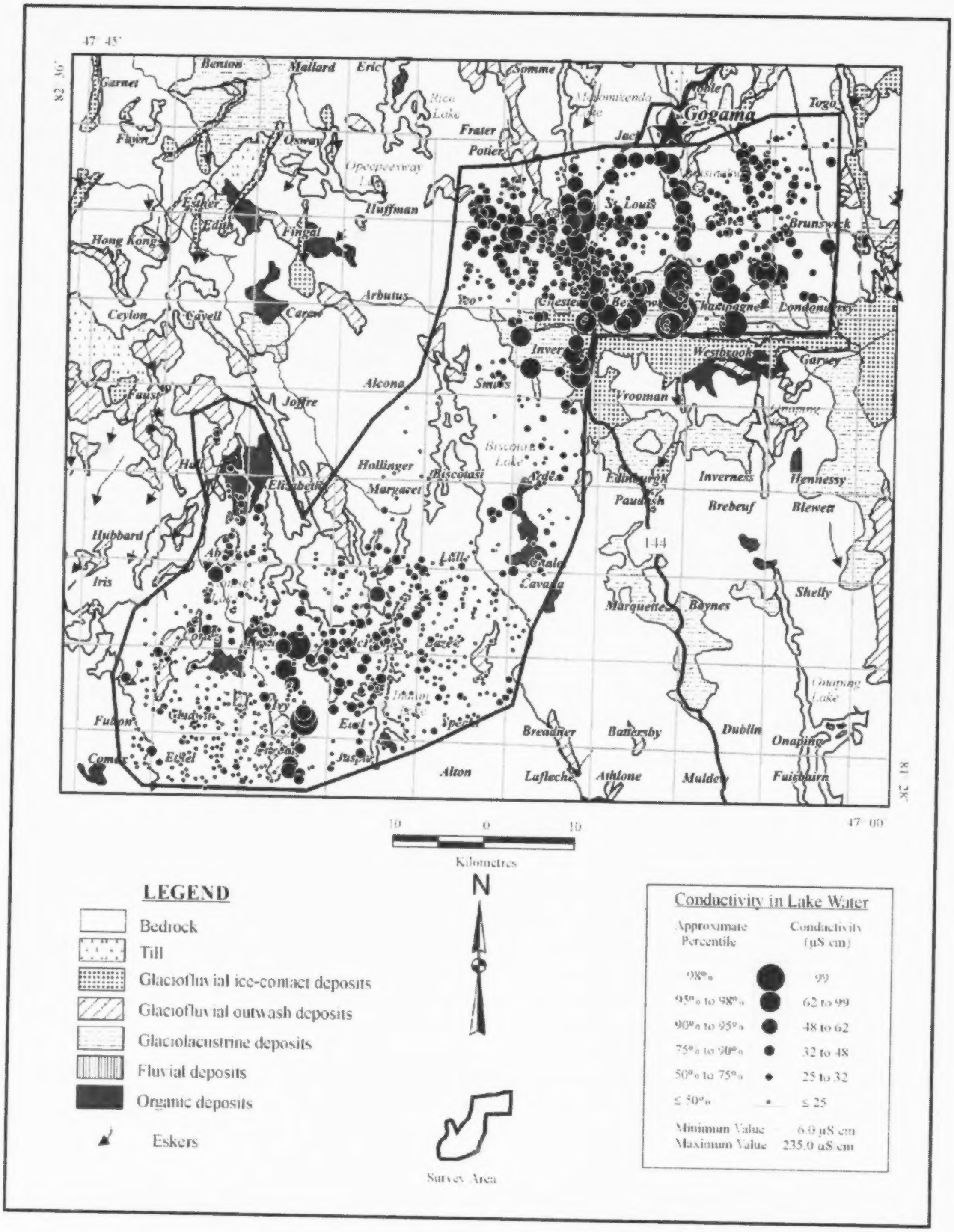
47° 45'
82° 36'
81° 28'
47° 00'
Benton
Mallard
Eric
Somme
Garnet
Rice Lake
Mattagami/Minisinakwa Lake
Noble
Gogama
Togo
Fawn
Osway
Frater
Potier
Jack
Opeepeesway Lake
St. Louis
Esker
Edith
Huffman
Hong Kong
Fingal
Brunswick
Arbutus
Ceylon
Cavell
Carew
Rio
Chester
Benneweis
Champagne
Londonderry
Inver
Westbrook
Garvey
Alcona
Smith
Fauquier
Joffre
Vrooman
Onaping
Hollinger
Biscotasi Lake
Hess
Elizabeth
Biscotasi
Margaret
Ardeé
Edinburgh
Inverness
Hennessy
Paudash
Brebeuf
Blewett
Hubbard
144
Iris
Abney
Lillie
Cavana
Shelly
Marquette
Baynes
Onaping Lake
Fulton
Gladwin
Ivy
Estel
Indian Lake
Breadner
Battersby
Dublin
Onaping
Comer
Esdel
Jasper
Alton
Laflèche
Athlone
Mulder
Fairbairn
10
0
10
Kilometres
N
LEGEND
Bedrock
Till
Glaciofluvial ice-contact deposits
Glaciofluvial outwash deposits
Glaciolacustrine deposits
Fluvial deposits
Organic deposits
Eskers
Survey Area
Conductivity in Lake Water
Approximate Percentile
Conductivity (µS/cm)
98%
99
95% to 98%
62 to 99
90% to 95%
48 to 62
75% to 90%
32 to 48
50% to 75%
25 to 32
≤ 50%
≤ 25
Minimum Value
6.0 µS/cm
Maximum Value
235.0 µS/cm

Figure 25.3. Generalized Quaternary geology and electrical conductivity in lake waters of the Biscotasi Lake survey area. Quaternary geology *after* Barnett, Henry and Babuin (1991).

SAMPLE PREPARATION AND ANALYTICAL PROGRAM

The organic lake sediments were placed in a breathable fabric sample bag and partially air dried in base camp prior to shipment to the analytical laboratory. The samples are freeze-dried to retain any volatile elements, partially pulverized and sieved to attain a –80 (<177 µm) mesh size fraction. Laboratory analysis of the –80 mesh fraction of the organic sediments will include nitric acid – aqua regia digestion of 1 g of sample material followed by inductively coupled plasma mass spectrometry (ICP–MS) and inductively coupled plasma optical emission spectrometry (ICP–OES) to determine approximately 50 trace elements. The nitric acid – aqua regia digestion technique attacks all the matrix constituents in the sample except for the silicate minerals and is therefore considered a nonselective, relatively strong partial extractant.

For each sample, approximately 15 g of prepared material will be pressed into briquettes and submitted for analysis by instrumental neutron activation (INAA) for Au and a suite of 33 other elements. Duplicates of samples and certified reference materials will be used to monitor the quality control of all analyses. Loss on ignition (LOI) is determined at 500°C, using an automated gravimetric technique.

The water samples were filtered through 0.45 µm syringe filters and acidified to 1% ultrapure nitric acid within 24 hours of collection. Direct aspiration ICP–MS will be used on the water samples to analyze for approximately 50 elements including major cation and anion species. Sample duplicates, blanks and certified reference standard SLRS-4 will be used to monitor the quality control of the water analyses.

PRELIMINARY RESULTS

The average electrical conductivity (EC) for surface waters sampled from the survey is 30.8 µS/cm with samples ranging from <10 to 235 µS/cm. Figure 25.3 illustrates the range of EC values across the study area. The EC values are plotted on a base of the generalized Quaternary geology of the Biscotasi Lake area (Barnett et al. 1991). In general, high electrical conductivity of lake waters in uncontaminated shield terrain is attributable to dissolved carbonate minerals from surficial sand and gravel deposits. Most of the higher EC values collected from the present survey occur over areas of glaciofluvial ice-contact deposits south of Gogama.

The pH of the surface waters ranged from 3.72 to 9.49 with an average pH of 6.83. The pH of surface waters for the study area is shown on Figure 25.2 plotted on a base of generalized bedrock geology (Ontario Geological Survey 1991). Many of the more alkaline lakes in the survey area occur with the higher EC values, south of Gogama. The presence of more alkaline conditions with higher EC values indicates probable dissolved carbonate minerals in the waters derived from the underlying glaciofluvial deposits. Lake waters with neutral to acidic pH values are underlain by intermediate to felsic intrusive complexes in areas with thin drift cover.

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Ontario Geological Survey 1991. Bedrock geology of Ontario, east-central sheet; Ontario Geological Survey, Map 2543, scale 1:1 000 000.

26. Project Unit 02-011. Eagle Lake Area High Density Regional Lake Sediment and Water Survey, Northwestern Ontario

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INTRODUCTION

Fieldwork for a high-density lake sediment and water geochemical survey in the Eagle Lake area of northwestern Ontario was carried out from June 17 to June 29 and August 8 to August 26, 2002. The survey area is located approximately 300 km northwest of Thunder Bay and is represented on National Topographic System (NTS) 1:50 000 scale map sheets 52F/11, 52F/13, 52F/14 and 52F/15. Figure26.1 shows the location of the survey area overlain on a base of bedrock geology. Lake sediment and/or water samples were collected at 932 sites, for an average density of 1 sample per 4.3 km^2. Glaciolacustrine sediments prevalent in the areas represented by sheets 52F/14 and 52F/15 resulted in relatively low sample densities of 1 sample per 8.4 km^2 and 10.5 km^2, respectively. The area represented by map sheets 52F/11 and 52F/13 have higher densities of 1 sample per 3.88 km^2 and 2.16 km^2, respectively, due to the rugged bedrock-controlled terrain.

The Eagle Lake area was selected for this type of survey for reasons including client interest, geology with favourable mineral potential and a lack of detailed geochemical exploration data for the region. The present survey lies immediately adjacent to the Sturgeon Lake – Wabigoon Lake survey (Russell 2001) and immediately south of an Operation Treasure Hunt lake sediment survey (Dyer 2000). The National Geochemical Reconnaissance (NGR) lake sediment program carried out by the Geological Survey of Canada in the 1970s covered this area (Hornbrook and Friske 1989), but at a much broader scale (an average of 1 sample per 13 km^2). The results of the current program will provide new regional geochemical data at a relatively high resolution.

REGIONAL GEOLOGIC SETTING

Bedrock Geology

The geology of the survey area is represented at a scale of 1:253 440 on an Ontario Geological Survey (OGS) Geological Compilation Series map (Blackburn 1981). In the western part of the survey area, the townships of MacNicol, Tustin, Bridges and Docker were mapped by Pryslak (1976) at a scale of 1:31 680. Breaks and Kuehner (1984) mapped the Eagle River – Ghost Lake area to the north and west of the town of Dryden at a scale of 1:31 680. Berger (1990) mapped Laval and Hartman townships, located at the eastern edge of the area, at a scale of 1:20 000. More recently, Beakhouse (2000, 2001) began a multiyear mapping program to examine the geology and mineral potential of the Wabigoon Lake area, which is partially contained in the eastern portion of the survey area. Breaks, Selway and Tindle (2001) highlight a number of regions within the present survey area with rare-element pegmatite potential.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.26-1 to 26-6.

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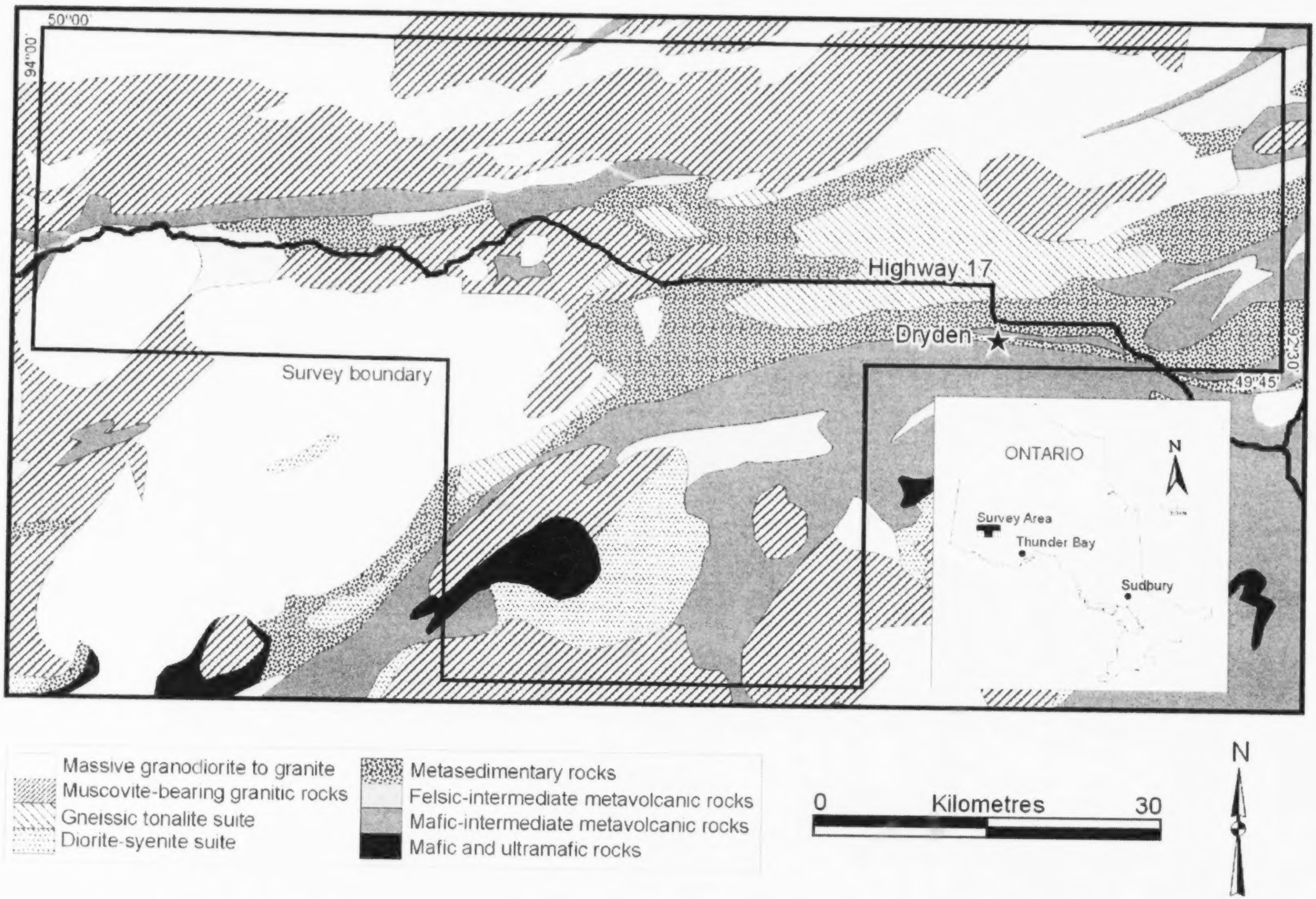
50°00'
94°00'
Highway 17
Dryden
92°30'
49°45'
Survey boundary
ONTARIO
N
Survey Area
Thunder Bay
Sudbury
Massive granodiorite to granite
Muscovite-bearing granitic rocks
Gneissic tonalite suite
Diorite-syenite suite
Metasedimentary rocks
Felsic-intermediate metavolcanic rocks
Mafic-intermediate metavolcanic rocks
Mafic and ultramafic rocks
0
Kilometres
30
N

Figure 26.1. Bedrock geology of the Eagle Lake area lake sediment and water geochemical survey. Geology *after* Ontario Geological Survey (1991).

Two distinct supracrustal belts occur in the survey area. In the Eagle Lake area, a belt of metavolcanic rocks forms the western expression of the arcuate Eagle–Wabigoon–Manitou Lakes greenstone belt (Blackburn et al. 1991). The stratigraphy of the Eagle Lake area consists of a lower unit of Fe-Mg tholeiite (Eagle Lake volcanics), which are unconformably overlain by a mixed tholeiitic and/or calc-alkaline unit (Lower Wabigoon volcanics). This middle unit is conformable with the overlying Upper Wabigoon volcanics, which consist of Fe-tholeiite and calc-alkaline rocks. The volcanic assemblage is intrusively bounded to the south by the Atikwa Batholith and to the north by the Wabigoon fault. The Mulcahy Lake intrusion, a layered mafic to ultramafic intrusion, lies to the southwest of the volcanic belt. Ages from Smith (1987) indicate that the Mulcahy Lake intrusion is younger than the volcanic assemblage, but predates emplacement of the Atikwa Batholith.

In the western part of the survey area, the Vermilion Bay greenstone belt strikes east-northeast for approximately 58 km with a maximum width of about 6.4 km near Medicine Lake. This belt appears to be an extension of the metasedimentary and mafic to intermediate metavolcanic rocks of the Lake of the Woods greenstone belt in the Kenora area. The Vermilion Bay greenstone belt consists of mafic to intermediate metavolcanic flows and pyroclastic rocks, which are complexly interlayered with metasedimentary rocks composed of greywacke, calc-silicate gneiss, massive calc-silicate rocks and iron formation (Pryslak 1976). The metasedimentary and metavolcanic rocks are intruded by various dikes, sills and irregular bodies ranging in composition from felsic to ultramafic. The northern contact between the greenstone belt and the granitic rocks is interpreted to be the division between the Wabigoon Subprovince to the south and the Winnipeg River Subprovince to the north (G.P. Beakhouse, OGS, personal communication, 2002). The southern part of the greenstone belt is intrusively bounded by the Dryberry Batholith, a multiphase granitic intrusion with ages ranging from 2716 to 2663 Ma.

Physiography and Quaternary Geology

Engineering geology terrain maps have been produced for the area at a scale of 1:100 000 (Roed 1980a, 1980b). These maps, developed mainly from the interpretation of aerial photographs, comprise the most detailed Quaternary mapping for the area. Relief in the survey area varies locally, although is generally less than 50 m. Topography in the survey area is controlled by the distribution of surficial sediments or erosion and faulting of the underlying bedrock.

Two distinct surficial landscapes cover the survey area. To the northeast of Eagle Lake–Vermilion Bay is an area with extensive deposits of clay, silt and sand deposited by glacial Lake Agassiz (Roed 1980a). Locally, these sediments produce areas of gentle topography and result in a decrease in the density of lakes. To the southwest and west, the landscape is bedrock dominated. Quaternary deposits consist of a thin veneer of sandy till (Roed 1980b). The Eagle–Finlayson Moraine separates these 2 areas. This moraine rises higher than 30 m above the surrounding landscape and extends for greater than 240 km, trending in a northwest direction (Zoltai 1961). The moraine is described in Barnett (1992) as consisting of sand and gravel; boulders in excess of 2 m were locally observed on the moraine surface during the present survey.

SAMPLING METHODS

Sampling of organic lake sediments was performed using a float-equipped Bell 206B helicopter. Where access was available and the number of samples warranted, some lakes were sampled from an aluminum boat with a 25-horsepower motor. An overall average of 13.5 lakes were sampled for each hour of helicopter time. The samples were collected using a gravity corer designed by the OGS. Samples were taken from deeper than 20 cm below the sediment–water interface (SWI) in order to minimize or avoid anthropogenic influences and SWI effects. These deeper sediments more accurately reflect geochemical effects, which may be traced back to the local geology. The samples were extruded from the collection tube into breathable fabric bags and then placed in a sealable plastic bag until the end of the sampling run.

Lake water samples were taken simultaneously with the collection of sediment samples. On lakes shallower than 3 m, the samples were collected at 0.5 m below the water surface; on lakes deeper than 3 m, the samples were collected at a depth of 2 m. A semi-automated water-sampling apparatus, developed by the OGS and consisting of a submersible pump, a water-quality meter (for measurement of parameters such as pH, temperature and conductivity), a sample bottle tray and a variety of hoses and valves, was used for sample collection. Lake water is pumped through the system in order to purge it prior to the collection of a sample and the recording of water-quality data. The water samples were kept cool immediately following collection and were processed (filtered and acidified) within 24 hours of collection.

Sample site locations were recorded using a GPS receiver mounted in the cockpit of the helicopter. Sediment sample information and descriptions were recorded on standardized forms and later entered into a computer. Waterquality data were recorded using a handheld data logger and transferred to a computer at the end of each sampling run.

SAMPLE PREPARATION AND ANALYTICAL METHODS

Lake sediment samples were partially air dried in porous collection bags while in the field. Upon arrival at the laboratory, the samples were freeze dried, partially pulverized in a ceramic ring mill and sieved to obtain the -80 mesh (<177 μm) size fraction. Laboratory analysis includes nitric acid – aqua regia digestion followed by inductively coupled plasma mass spectrometry (ICP–MS) and inductively coupled plasma optical emission spectrometry (ICP–OES) for the determination of approximately 50 trace and major elements. Nitric acid – aqua regia digestion attacks all sample matrix constituents, except for silicate minerals, and, therefore, is considered a nonselective, relatively strong partial extractant. Approximately 15 g of sample pulp are pressed into briquettes prior to analysis by instrumental neutron activation analysis (INAA) for Au and 34 other elements. Loss on ignition (LOI) is determined at 500°C using an automated gravimetric technique. Quality control is monitored through the use of certified reference materials placed regularly through the sample sequence and randomy taken sample pulp duplicates.

Water samples were passed through 0.45 μm syringe filters and acidified to ~1% ultrapure nitric acid within 24 hours of collection. Analysis of water was completed by direct aspiration ICP–MS to determine approximately 50 elements. Quality of the analyses is monitored through the use of certified reference standard SLRS-4 and random sample duplicates.

PRELIMINARY RESULTS

Electrical conductivity values in lake waters in the survey area range from less than 10 μS/cm to 210 μS/cm, averaging 25 μS/cm. Figure26.2 shows the distribution of conductivity in lake water across the study area. As the surficial cover in the area is not extensive, bedrock geology is the primary factor contributing to these values. Most of the conductivity values in the 90th percentile of the data set (>44 μS/cm) occur in areas underlain by or in close proximity to bedrock mapped as either metavolcanic or metasedimentary rocks. The lower values of the data set occur in primarily granitic bedrock areas. It should be noted that some of the highest values are found in close proximity to roads or highways, which may suggest some influence from contaminants (road salt, etc.) from these sources.

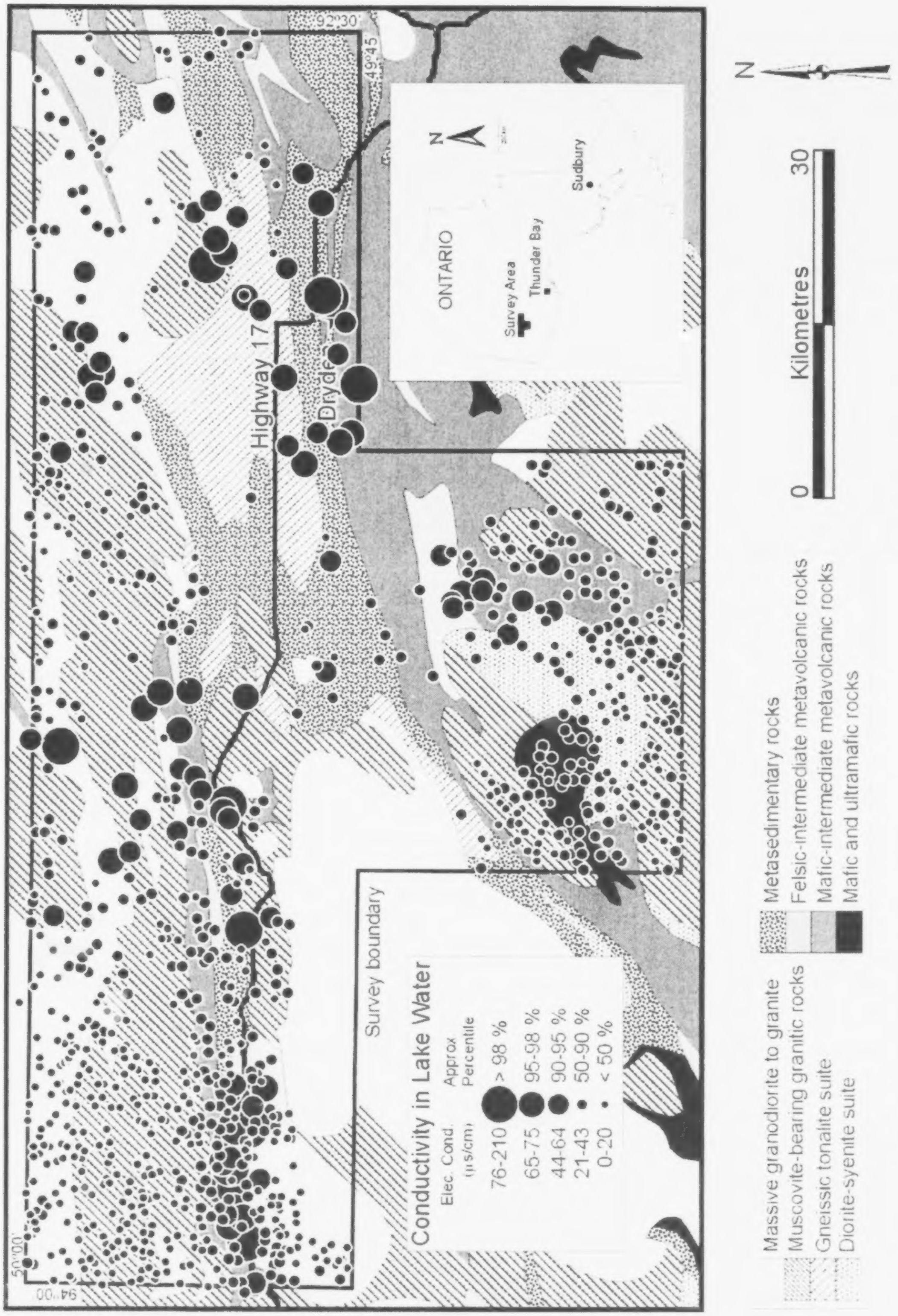
92°30'
49°45'
50°00'
94°00'
Highway 17
Dryden
ONTARIO
Survey Area
Thunder Bay
Sudbury
N
Survey boundary
Conductivity in Lake Water
Elec. Cond. (µs/cm)
Approx. Percentile
76-210 > 98 %
65-75 95-98 %
44-64 90-95 %
21-43 50-90 %
0-20 < 50 %
0
Kilometres
30
N
Massive granodiorite to granite
Muscovite-bearing granitic rocks
Gneissic tonalite suite
Diorite-syenite suite
Metasedimentary rocks
Felsic-intermediate metavolcanic rocks
Mafic-intermediate metavolcanic rocks
Mafic and ultramafic rocks

Figure 26.2. Bedrock geology and electrical conductivity in lake waters.

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27. Project Unit 99-318. Thick Overburden Geochemical Methods: Studies over Volcanogenic Massive Sulphide Mineralization and Kimberlite

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[3]Geological Survey of Canada, Ottawa, Ontario
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INTRODUCTION

Geochemical exploration methods for use in areas of thick glacial overburden have been a longstanding objective of the Ontario Geological Survey (OGS). Recently, significant advances have been made in this area by the OGS and its partners (Jackson 1995; Bajc 1998; Hamilton and McClenaghan 1998; Hamilton and Cranston 2000; Hamilton 2000a). Among these advances are improved methods for the detection of electrical and electrochemical (redox) fields over mineralization that have shown the existence of chemically reduced "columns" over mineralization. Previously, these chemically reduced columns had only been predicted to occur (Hamilton 1998; Hamilton 2000b). Also, the application of better sample collection protocols for analysis by partial extraction techniques has provided unequivocal geochemical responses over mineralization covered by up to 50 m of glacial sediment. Several publications, currently in advanced stages of preparation, outline the new electrical and electrochemical techniques and results over gold mineralization at the "Marsh Zone", near Matheson, Ontario and volcanogenic massive sulphide (VMS) mineralization at the "Cross Lake" property, near Timmins.

Since 1999, most of the work done by the OGS on these methods has been part of the "Deep-Penetrating Geochemistry" project sponsored, in part, by the Canadian Association of Mining Industry Research Organizations (CAMIRO). That project is largely complete and is currently in the public reporting stage. The work was so successful that a proposal for continued investigation was made jointly by the Geological Survey of Canada (GSC) and the OGS to the Ontario Mineral Exploration Technologies (OMET) program for continued funding. This proposal, which includes CAMIRO and industry collaboration, was approved and is now underway. Much of the work carried out during the 2002 field season was under the resulting OMET project, entitled "Three-Dimensional Geochemistry in the Abitibi: Development of Geochemical Exploration Methods". Some exciting preliminary results from this project are described below. Those results were collected during a transition period between the CAMIRO and OMET projects with resources provided by both.

In the 2002 field season, the new techniques were also tested over kimberlites in similar thick glacial overburden environments. This project, entitled "Enhancement of kimberlite exploration methods" was largely funded by the GSC under the Targeted Geoscience Initiatives (TGI) program. It involves sampling of surface soils for geochemical analysis by partial extractions; surface spontaneous potential (SP) and platinum spontaneous potential (PtSP) testing and water sampling of existing boreholes in kimberlite to determine how the kimberlite affects the groundwater environment at source. Preliminary results are

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Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.27-1 to 27-17.

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described below. Since the 2 projects are different initiatives and separately funded, they are described separately below. However, they are both part of the overall initiative by the OGS and its partners to improve geochemical detection techniques in areas of thick glacial overburden.

PARTIAL EXTRACTION TECHNIQUES: RESULTS FROM A TRENCH DUG IN CLAY SOILS OVER VOLCANOGENIC MASSIVE SULPHIDE MINERALIZATION

Background

The CAMIRO Deep-Penetrating Geochemistry (DPG) project at Cross Lake (Figure 27.1), near Timmins in northeastern Ontario, commenced in 1999 by sampling B-horizon soils and humus along Line 6, where VMS mineralization is covered by approximately 30 m of clay and silt and Line 40, where similar mineralization is covered by approximately 50 m of sand and clay. The soil samples comprised a thick section of B-horizon vertical interval and were analyzed by several methods representing weak to strong extractions. Humus samples were analyzed after extraction by the methods that are most frequently used for this material: sodium pyrophosphate and aqua regia. None of the data showed a convincing response over the mineralization on either line. In 1999, we also collected a separate sample at a constant depth of 10 to 25 cm below the A_0 horizon for analysis by the Mobile Metal Ion™ (MMI)-A method. This gave distinctively strong anomalies for zinc over the mineralization on both lines.

An objective in returning to this area in 2000 was to resolve the enigma of the poor response of the B-horizon samples. During this visit, we sampled at 2 depths within the B-horizon: the upper 10 cm and the 10 to 20 cm interval. Results indicated that the 0 to 10 cm interval has a strong anomaly for zinc and cadmium by 3 "weak" leaches: ammonium acetate, Enzyme Leach^{SM} and MMI, whereas the lower

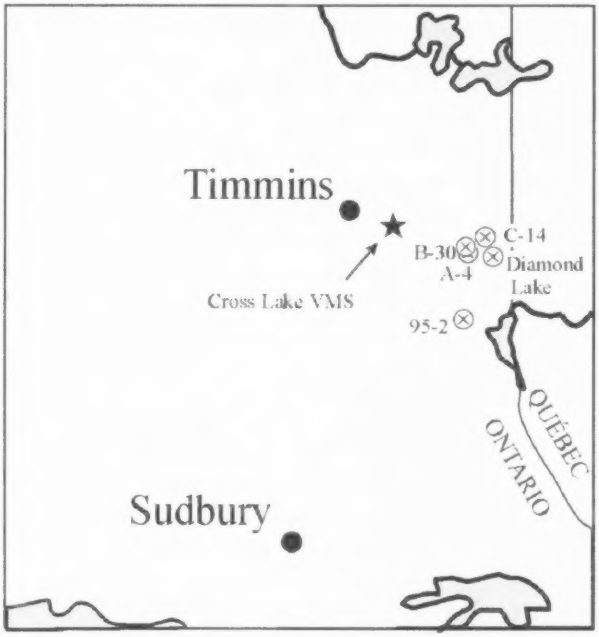


Figure 27.1. Location of study areas.

interval is “flat”. The results shown in Figure 27.2a are typical of all 3 leaches. Also, there is a sharp decrease in the pH of the B-horizon soil over the mineralization (Figure 27.2b) and this lower pH is reflected in an apparent loss of $CaCO_3$ and magnesium-rich carbonates from the soil overlying the VMS subcrop.

The decrease in pH is consistent with the results from the studies by the OGS on the electrogeochemistry and hydrogeology of the thick cover of glacial sediments overlying mineralization. Figure 27.3 illustrates a model derived from these studies. It shows a reduced column rising through the clays, bringing metals and other reduced materials towards the surface. In the saturated zone below the water table, access of oxygen to the reduced materials is limited, but above the water table, infiltration of oxygen permits oxidation, for example,

$$Fe^{2+} + {}^{1}/_{2}O_2 + 2H_2O \rightarrow Fe(OH)_3 + H^+$$

The hydrogen ions formed by the oxidation of reduced species produces the acidic conditions in the vadose zone above the reduced column.

In 2001, as the DPG project neared an end, discussions were held regarding new projects for 2002 that might continue work at Cross Lake and elsewhere in the Abitibi belt. At that time, the cause for the restriction of anomalies to the uppermost soil horizons remained enigmatic. This suggested a need for more detailed studies of the vertical and horizontal distribution of elements and of redox and pH distributions over the mineralization. In September 2001, a trench 1.5 m deep was dug over a 160 m length of Line 6 (Figure 27.4a). The intent was to initiate the trench studies as part of the CAMIRO Deep-Penetrating Geochemistry project and continue the work into a successor project.

The trench was centred over the mineralized subcrop, which is at 180 to 200 m along Line 6. Samples were taken down vertical profiles at 10 cm intervals (0 to 10, 10 to 20, etc.) from the surface to 60 cm depth (*see* Figure 27.4a). Four profiles were sampled to 100 cm depth (Figure 27.4b). In addition to samples for geochemical analysis, samples were collected for oxidation–reduction potential (ORP) and pH measurements; these results will be reported separately. A total of 33 profiles were sampled at approximately 5 m horizontal intervals. After sampling was completed and the trench backfilled, the precise locations of the profiles were established by surveying. Samples were dried and sieved to –80 mesh and analyzed after aqua regia digestion at Acme Laboratories, Vancouver, British Columbia, and by the Enzyme Leach method at Actlabs, Ancaster, Ontario. The samples will be analyzed by additional methods as part of the successor project sponsored by the Ontario Mineral Exploration Technologies (OMET) program and CAMIRO (Hall 2002).

Effect of Change in pH

The most dramatic effect of the oxidation of reduced material above the water table is acidification of the soil and clay. Figure 27.5a shows a zone of lower pH about 70 m wide and 60 cm deep directly above the VMS subcrop. Away from mineralization, the clay cover and soil derived from it are calcareous, with a pH ranging from neutral to weakly alkaline. In the acidified zone above the reduced column, the pH falls to as low as 5.4. The effect of acidification is to dissolve $CaCO_3$ and entirely remove the calcium laterally to the flanks of the zone, where it is re-precipitated where the pH is higher (Figure 27.5b). Acidification also appears to modify the non-carbonate fraction of the clay. Uranium, as extracted by Enzyme Leach, is higher within the acidified zone (Figure 27.6a). It may be that the acid has modified the clay structure making uranium more accessible for leaching, however, the element has not migrated away from this zone. Uranium, which dissolves as an anion, is not mobile under acidic conditions. By contrast, copper, which dissolves as Cu^{2+}, is depleted within the acidic zone (Figure 27.6b).

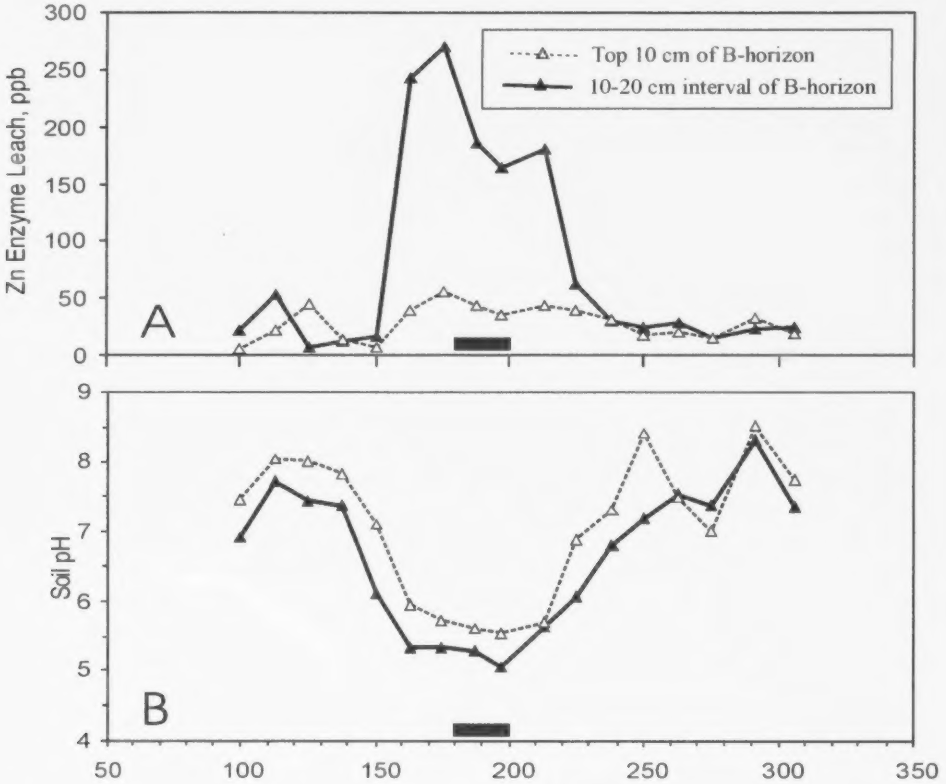


Figure 27.2. Zinc by Enzyme Leach and pH in B-horizon soils, Line 6SE, Cross Lake. Horizontal scale in metres. Black rectangle represents the subcrop of VMS mineralization.

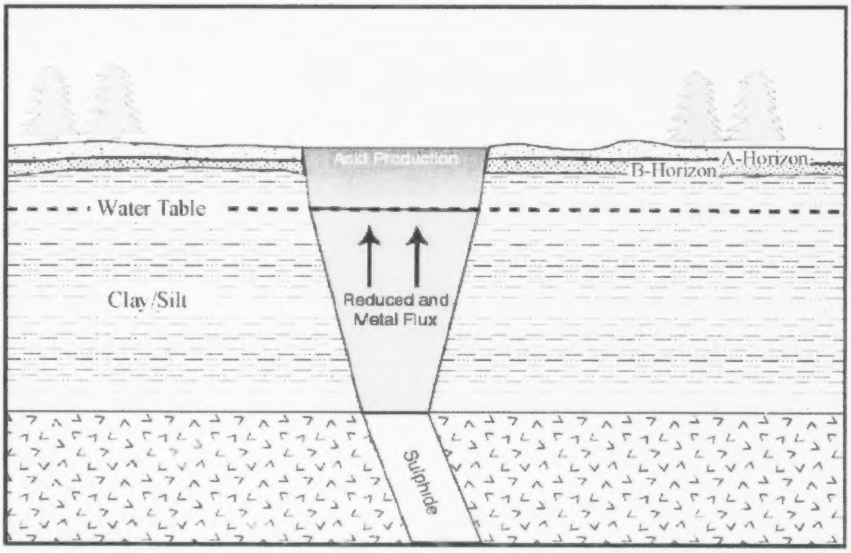

Acid Production
A-Horizon
B-Horizon
Water Table
Clay/Silt
Reduced and Metal Flux
Sulphide

Figure 27.3. Model for the dispersion of reduced materials from a sulphide body through clay cover.

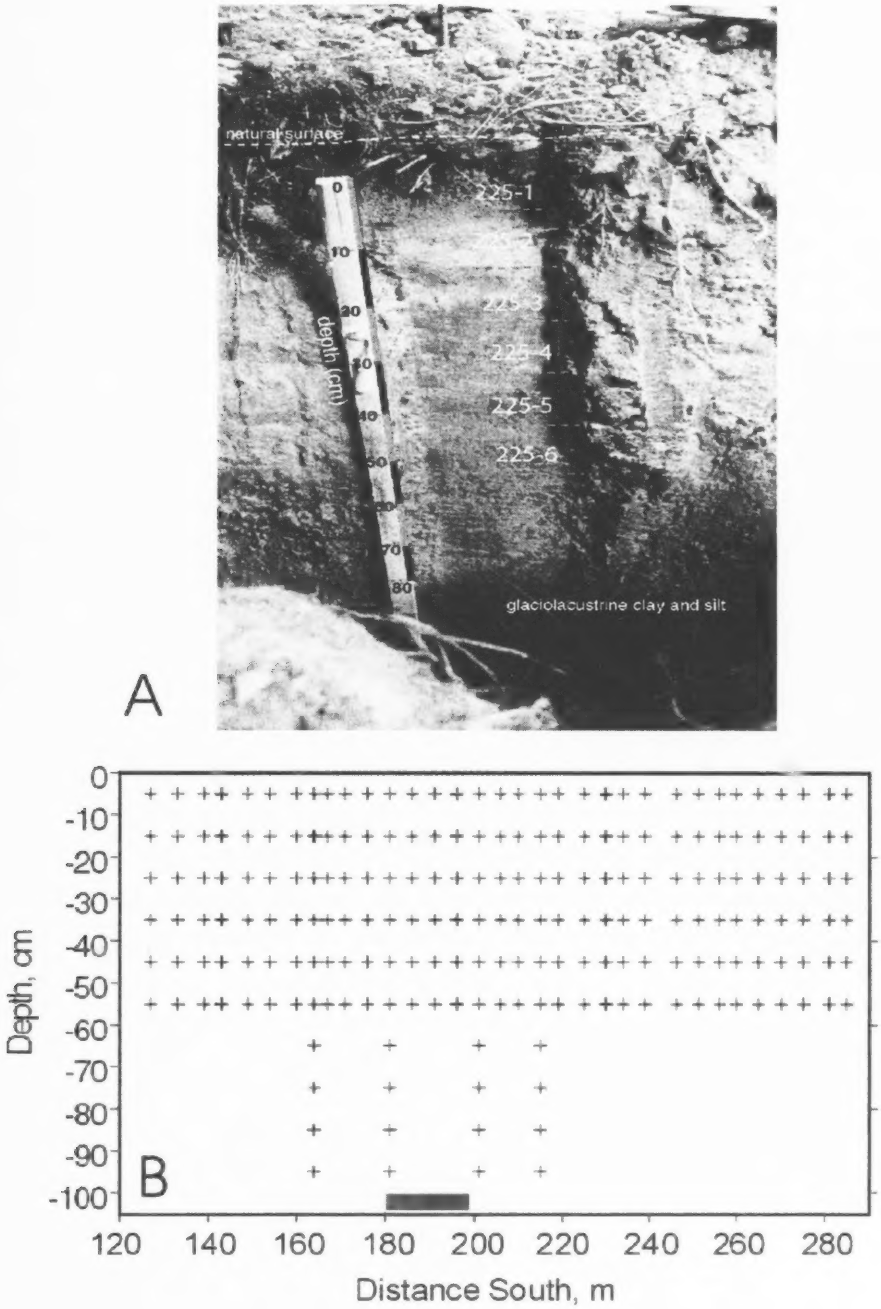

natural surface
225-1
225-2
225-3
225-4
225-5
225-6
depth (cm)
0
10
20
30
40
50
60
70
80
glaciolacustrine clay and silt
A
B
Depth, cm
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
120
140
160
180
200
220
240
260
280
Distance South, m

Figure 27.4. Trench sampling: (A) typical sampled soil profile in the trench and (B) sample locations (+) within the trench. Depths shown are the midpoints of the interval sampled.

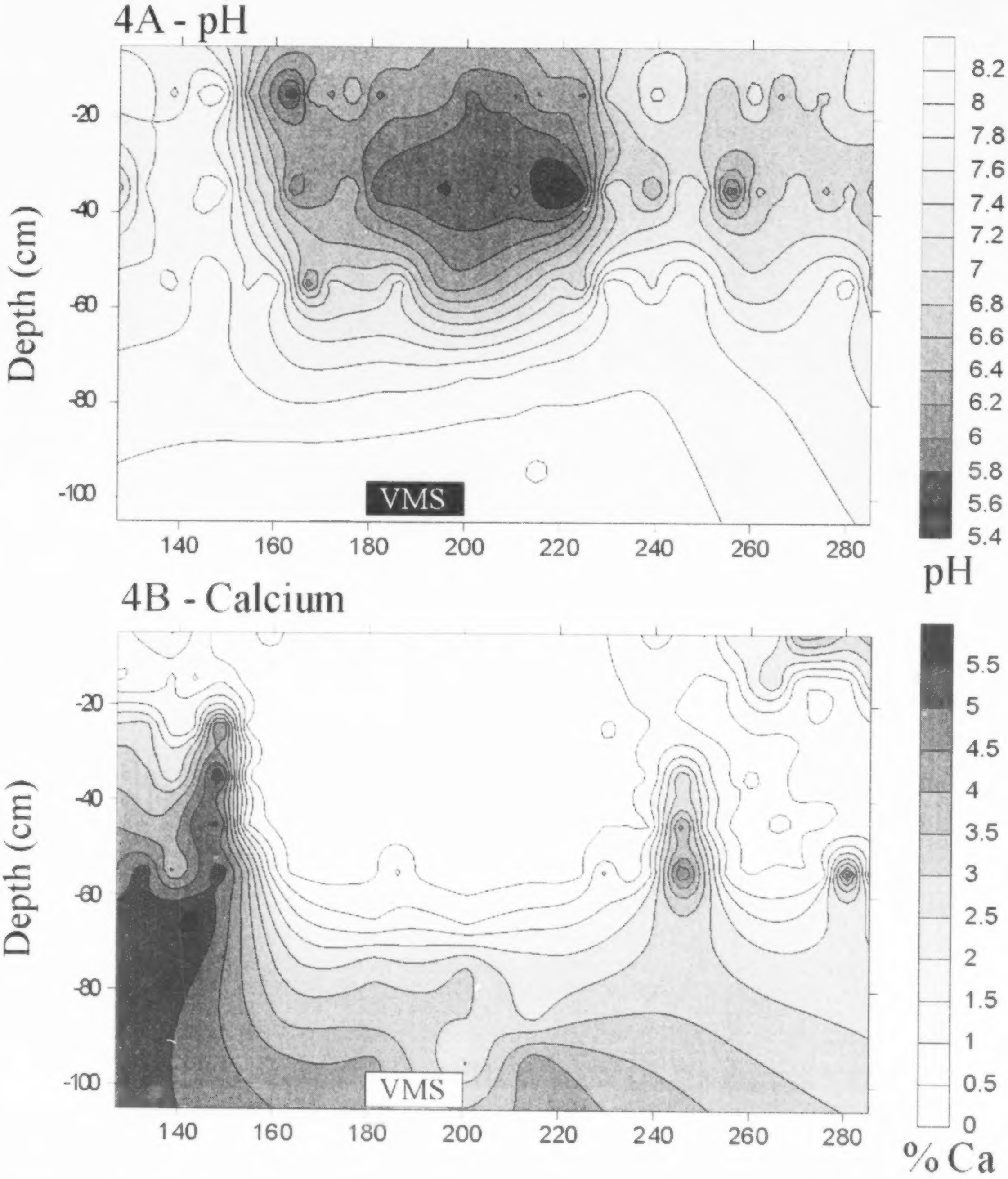
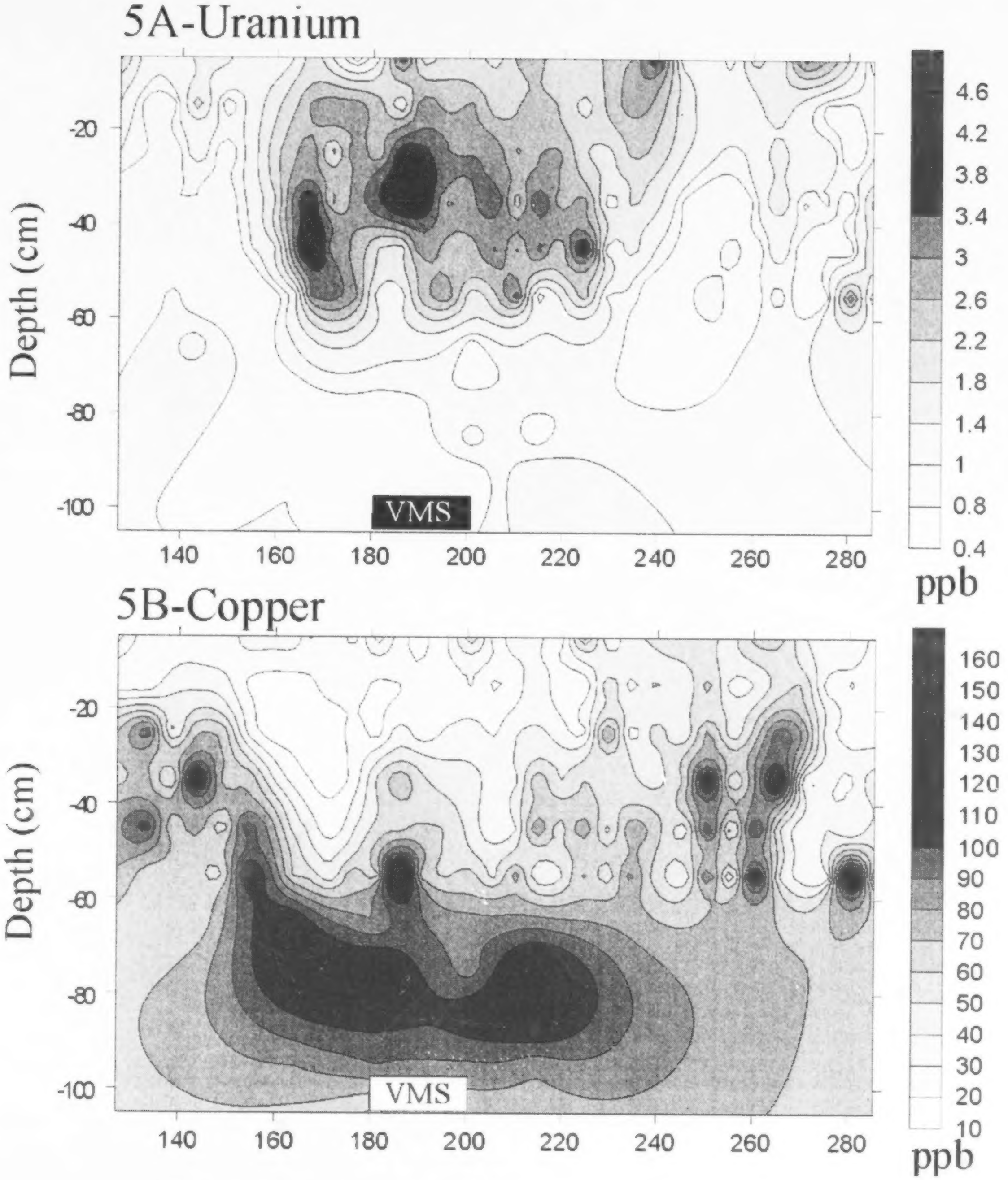


Figure 27.5. Soil slurry pH (A) and % Ca (B) by aqua regia of Line 6 trench samples. Note that on this and other contour plots, the upper margin is at 5 cm depth, the midpoint of the 0 to10 cm sample interval.



5A-Uranium

5B-Copper

Figure 27.6. Uranium (A) and copper (B) in ppb by Enzyme Leach – Line 6 trench samples.

Distribution of Zinc

Figure 27.7a is a contour plot of zinc by Enzyme Leach in the trench samples. A striking feature is that this readily extractable zinc is largely concentrated near the surface, distributed through a variety of soil horizons. There is a large range in the data. Much of the soil below 20 cm depth contains less than 50 ppb Zn, whereas samples from the 0 to 10 cm interval contain up to 1440 ppb Zn. Figure 27.7b displays the zinc results as posted symbols, together with letters indicating the predominant soil type for the samples collected in the top 10 cm. This shows that the highest values occur in humus samples directly above the VMS subcrop, whereas humus samples from the peripheries of the trench have lower contents of this element. Samples dominated by other soil types, A1, Ae and B, in the 0 to 10 cm interval also show high values above the VMS mineralization.

Figures 27.8 and 27.9 relate the data for zinc obtained on the B-horizon samples collected in 2000 to the data for this element obtained from the trench samples. In 2000, 2 samples of B-horizon were collected at 12.5 m intervals along Line 6 from 100 m south to 306 m south. The upper 10 cm of the B-horizon and the 10 to 20 cm interval of the B-horizon were sampled. In Figure 27.8, the location of these sample pairs are superimposed on the zinc contour plot for the trench shown in Figure 27.7a, with the results for the 2000 samples by Enzyme Leach shown above. Figure 27.9 is a similar plot, but with the MMI results shown for the samples collected in 2000. Note that the depth to the top of the B-horizon increases near the southern part of the trench because of a thick development of humus and/or peat and A1 and Ae material in a low, wet area. These comparisons show that most of the upper B-horizon collected in 2000 intersected the top 20 cm of the trench profile that is enriched in zinc. Thus, these samples gave a strong anomaly for zinc both by Enzyme Leach and MMI, although the absolute contents measured by the 2 extractions are substantially different. The lower B-horizon samples collected in 2000 "missed" the enriched upper part of the profile and do not show consistent anomalies over the mineralization. For comparison, the analyses by Enzyme Leach for the humus, upper B- and lower B-horizon samples collected in the trench in 2001 are shown in Figure 27.10. In comparing the B-horizon results by Enzyme Leach for the years 2000 (*see* Figure 27.8) with that for 2001 (*see* Figure 27.10), it should be noted that the samples collected in 2000 contain B-horizon material only; the 2001 trench results are for intervals that may contain mixtures of soil types, with B-horizon material being dominant.

If zinc is enriched in the near-surface soil horizons, most particularly in humus, why did the humus samples collected in 1999 not give a distinctive anomaly over the mineralized subcrop? The 1999 humus samples were analyzed after extraction with aqua regia and after extraction with sodium pyrophosphate, the 2 reagents most widely used for the analysis of this material. Figure 27.11 displays a plot of zinc in the 1999 humus samples after extraction with sodium pyrophosphate. The amounts so extracted range from 23 400 to 149 500 ppb Zn, the latter number being 100 times greater than the maximum value for humus by Enzyme Leach. Aqua regia extracts even more zinc from the humus, up to 247 900 ppb Zn. Thus, humus along Line 6 contains substantial amounts of zinc, but it appears that only a small fraction of this amount, extracted by "weak" leaches, provides a distinctive indicator of buried mineralization. The great majority of the zinc present in the humus is of "endogenic" origin, presumably derived from the clay substrate. This feature may be analogous to that for the soil samples reported from Gaby Sur (Cameron and Leybourne 2001). For these samples, analyses for copper by a leach of intermediate strength, cold hydroxylamine hydrochloride, are dominated by endogenic components, such that the signal from the underlying deposit is not apparent. But a water-soluble phase of this element, minor in amount to that extracted by stronger reagents, provides a clear indicator of the mineralization.

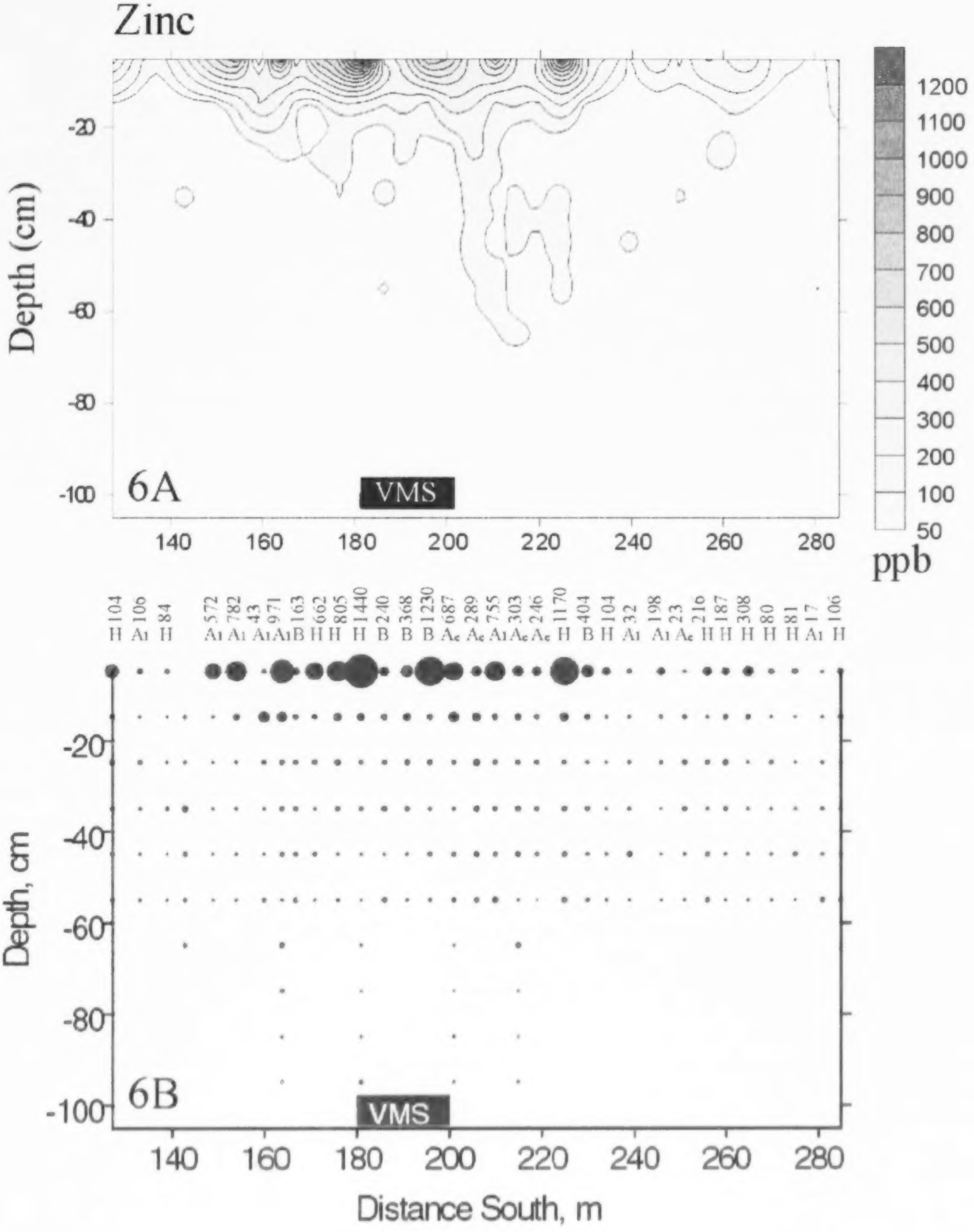


Figure 27.7. Contour (A) and bubble (B) plots of zinc by Enzyme Leach in the trench by sample location. The size of each circle indicates a progressive increase from less than the 10 ppb detection limit to the maximum of 1440 ppb Zn. The letters at the top indicate the predominant lithology of the soil sampled from the upper 10 cm interval and the amount of Zn in ppb in samples from this interval. Abbreviations: H, humus; A1, organic-rich mineral soil; Ae, elluviated horizon; B, B-horizon.

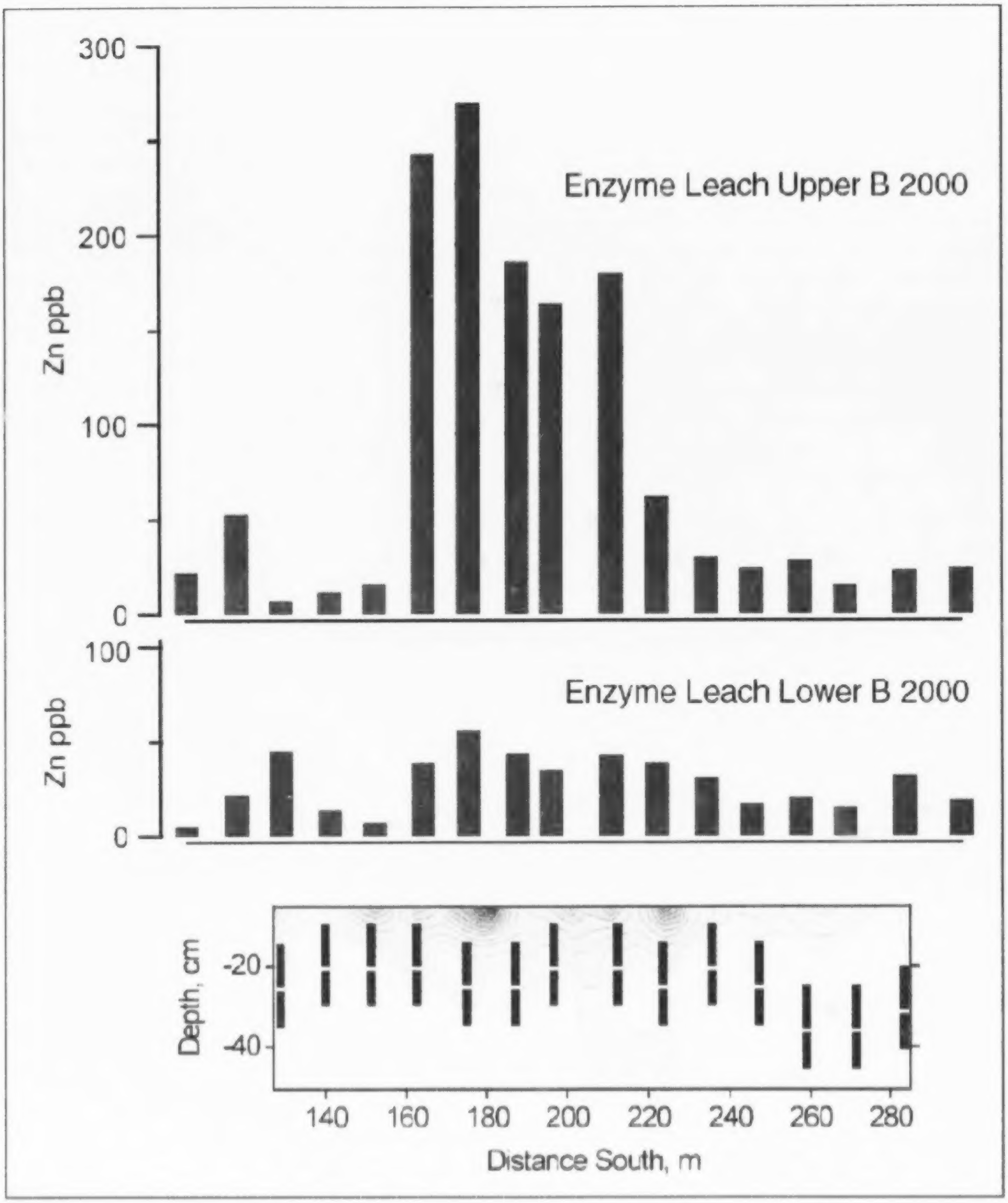


Figure 27.8. In 2000, samples were collected from the upper 10 cm of the B-horizon and from the 10 to 20 cm interval of the B-horizon. The Enzyme Leach results for these samples are shown in the upper 2 plots. In the lower plot, contours are shown for zinc by Enzyme Leach in the 2001 trench samples (*see* Figure 27.7), with black lines indicating the relative position of the samples collected in 2000. Note that the traverse sampled in 2000 is longer than the trench, so that in 2000 an additional 2 samples were collected north of the trench location and 1 additional sample to the south of the trench. The legend for the contour intervals of zinc is shown in Figure 27.7.

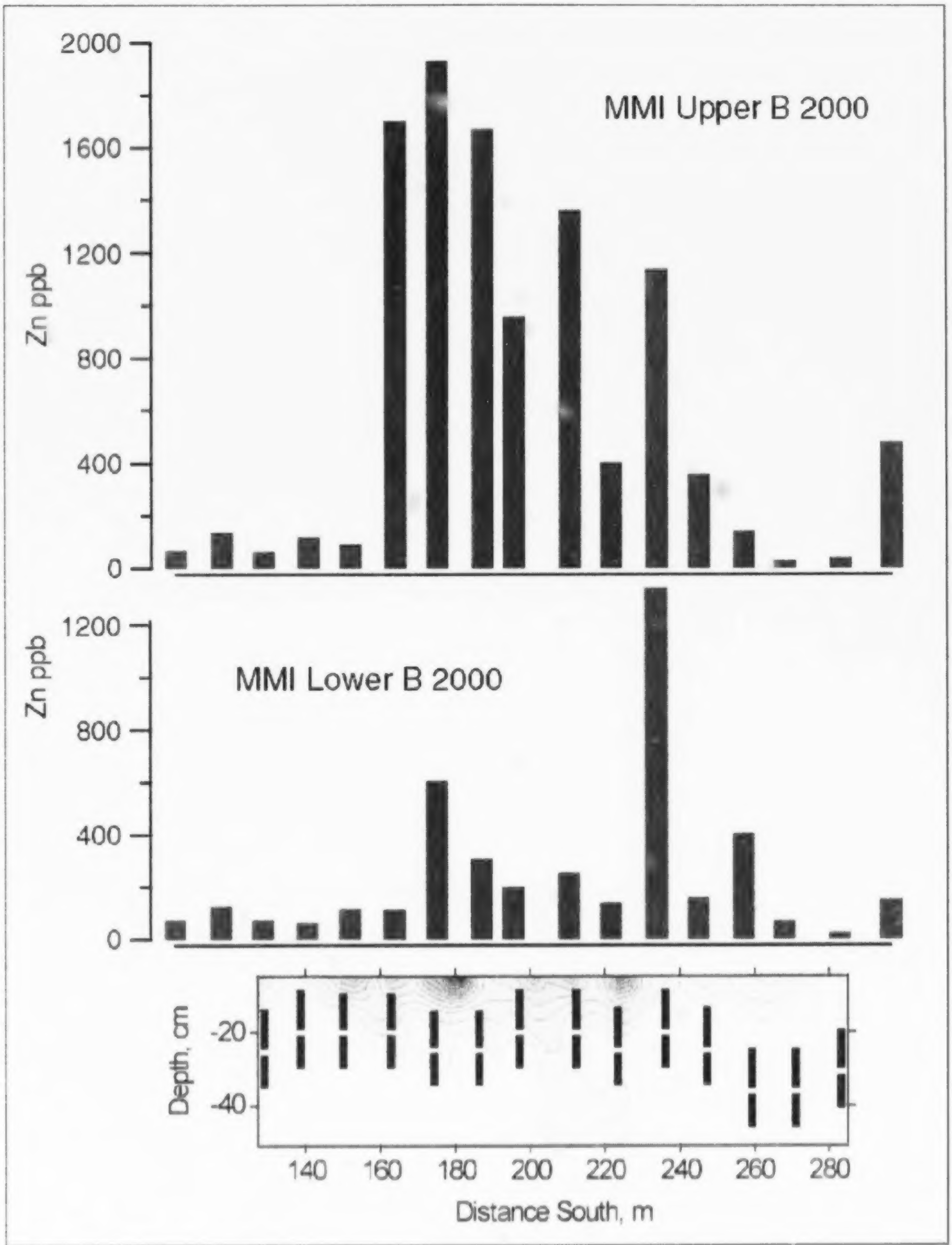


Figure 27.9. In 2000, samples were collected from the upper 10 cm of the B-horizon and from the 10 to 20 cm interval of the B-horizon. The Mobile Metal Ion™ (MMI) results for these samples are shown in the upper 2 plots. In the lower plot, contours are shown for zinc by Enzyme Leach in the 2001 trench samples (*see* Figure 27.7), with black lines indicating the relative position of the samples collected in 2000. Note that the traverse sampled in 2000 is longer than the trench, so that an additional 2 samples were collected north of the trench location and 1 additional sample to the south of the trench. The legend for the contour intervals of zinc is shown in Figure 27.7.

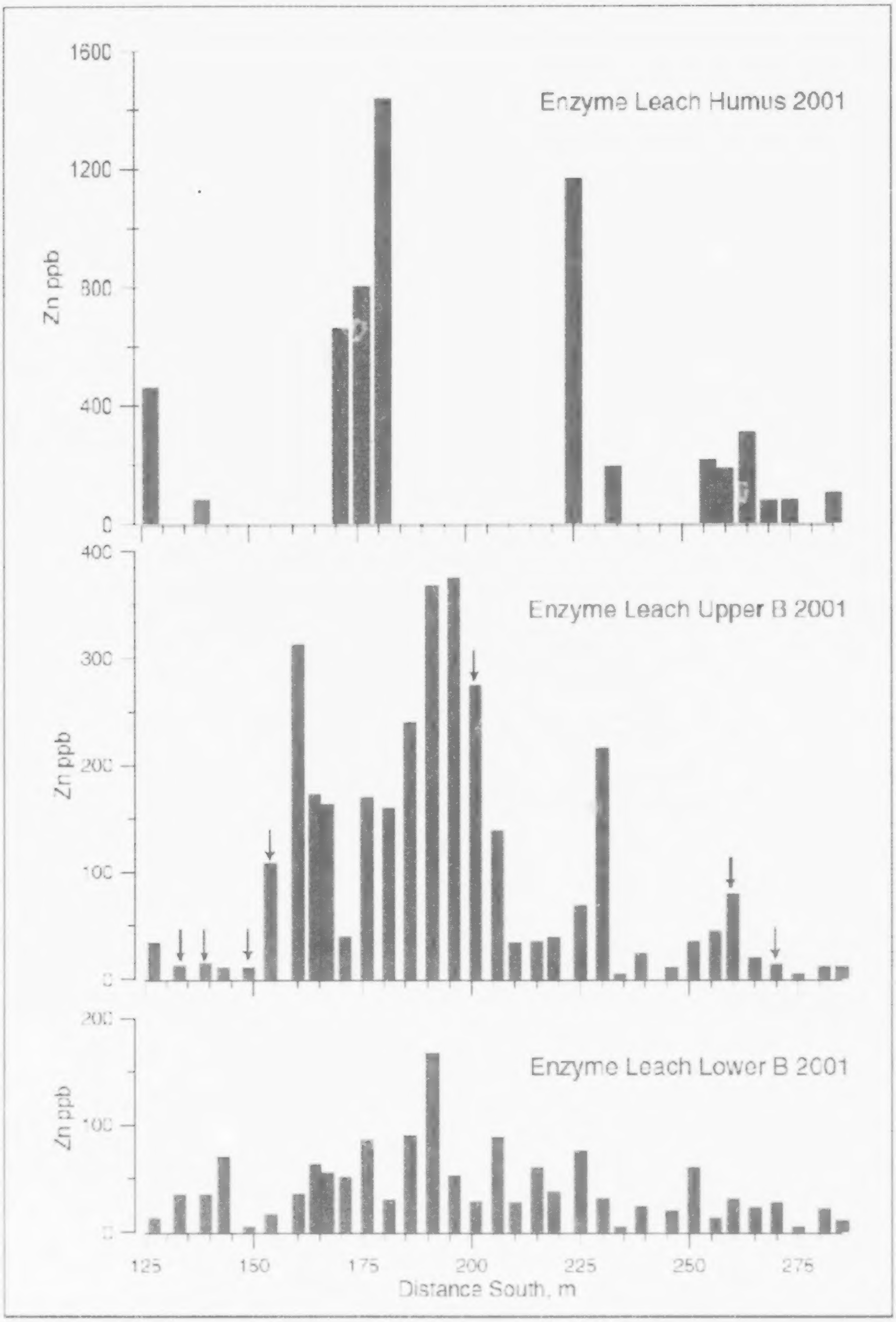


Figure 27.10. Plots of zinc in humus samples and the 0 to10 cm and 10 to 20 cm intervals of B-horizon in samples collected in 2001 from trench profiles. Not all profiles had humus. In some profiles, a specific B-horizon sample characterized by a reddish iron oxide colouration was not identified in the field. For these profiles, shown by the arrows on the middle plot, the 0 to 10 cm and 10 to20 cm intervals below the A-horizon were used for the plots.

Ongoing Work: Trench Selective Leach Data

Only a few highlights of the data collected as part of the trench work are presented in this report, more exhaustive interpretation will be carried out by the successor project funded by OMET (Hall 2002), which is presently applying other extraction methods to the samples. The latter project will face the interesting tasks of examining the processes that cause zinc, the principal mobile indicator of the VMS mineralization, to accumulate so close to the surface (cadmium also shows a similar distribution) and to determine the leach that most effectively maximizes the anomaly to background contrast for the humus samples. The OMET study includes a second trench, carried out in sand on Line 40 and a resampling of Line 6 for bacteriological studies. The preliminary ORP data from that line show such remarkable fluctuations and such a good spatial correlation with metal anomalies that bacteria are likely involved in the fixation of metals. This will be investigated in collaboration with Dr. G. Southam of the University of Western Ontario.

Another part of the OMET project includes sampling at the nearby gold property, the "Marsh Zone". The purpose of this is to obtain similar profile data to those collected at Cross Lake, to determine exactly where, and ultimately why, metals are accumulating in the shallow near-surface peat.

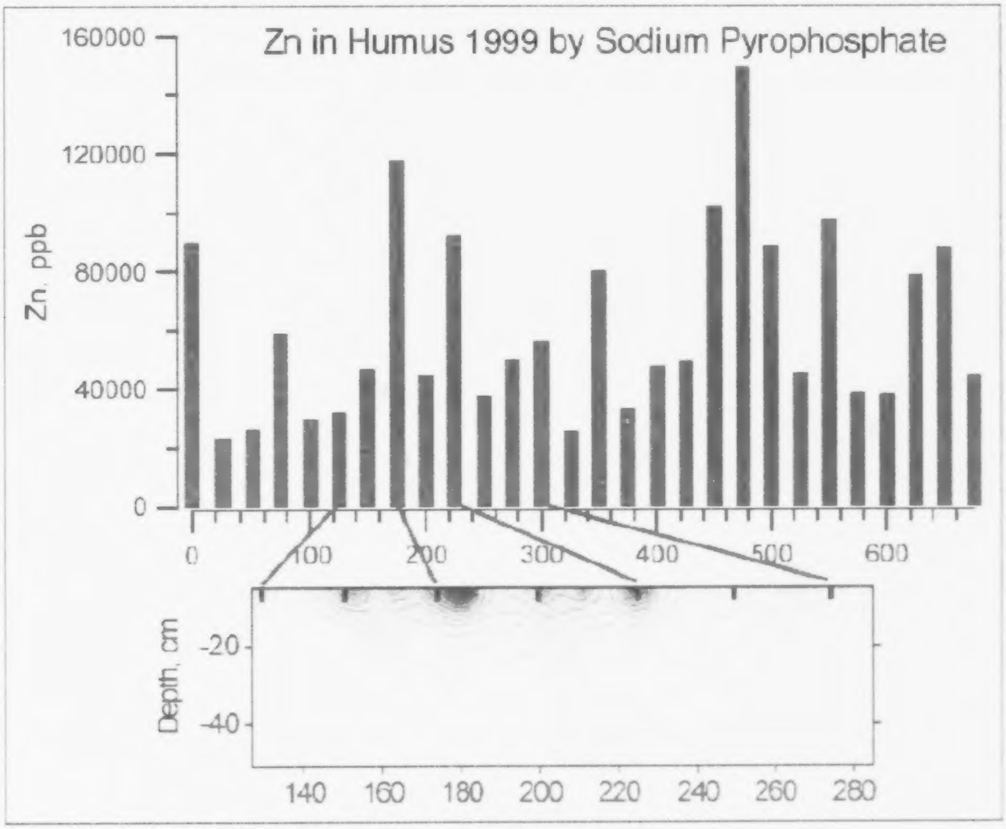


Figure 27.11. In 1999, samples of humus were collected at 25 m intervals along the entire 675 m length of Line 6. The samples were extracted by sodium pyrophosphate and aqua regia. The analyses for zinc by sodium pyrophosphate are shown in this figure relative to their approximate location along the trench. The contour plot is for zinc by Enzyme Leach in the trench samples; see legend for the contour intervals in Figure 27.7. In this and similar figures, the numbers along the x-axis represent the distance south along Line 6 in metres.

DEEP-PENETRATING GEOCHEMISTRY STUDIES OVER KIMBERLITE

Kimberlite contains abundant ultramafic minerals and during weathering should impart electrochemically reducing and high-pH conditions to surrounding surficial materials (groundwater, sediments, etc.). The typical weathering sequence of ultramafic rocks (Clark 1987) is as follows:

1. Dissolution of ultramafic minerals (olivine and pyroxene)

   Olivine dissolution:
   $$FeMgSiO_4 + 4H^+ \rightarrow Fe^{2+} + Mg^{2+} + H_4SiO_{4(aq)}$$

   Pyroxene (Hypersthene) dissolution:
   $$(Ca,Mg)SiO_3 + 2H^+ + H_2O \rightarrow \tfrac{1}{2}Ca^{2+} + \tfrac{1}{2}Mg^{2+} + H_4SiO_{4(aq)}$$

   As these reactions proceed, the result is increasing pH, as H^+ is consumed, and increasing concentrations of Ca^{2+}, Mg^{2+} and Fe^{2+}.

2. The increasing pH results in precipitation of carbonates early during the process and almost complete removal of CO_3^{2-} from solution. To some extent, the high Mg^{2+} and silicic acid result in low temperature serpentinization and the production of crysotile:

   serpentine production:
   $$3Mg^{2+} + 2H_4SiO_4 + H_2O \rightarrow Mg_3Si_2O_5(OH)_4 + 6H^+$$

   If this reaction were to proceed fully, the water would be neutralized. However, under low-temperature conditions, the reaction rate is slow enough that dissolution of the primary minerals is greatly favoured and the groundwater becomes supersaturated with respect to crysotile and becomes increasingly alkaline.

3. Iron released during dissolution of olivine and other mafic minerals quickly consumes any available oxygen, resulting in increasing $Fe^{2+}{}_{(aq)}$ and decreasing Eh. Eventually, with the low Eh and high pH, the groundwater in contact with the ultramafic rocks approaches the limit of water stability and begins to reduce water (or hydroxyl):

   $$2Fe(OH)^+ + 2OH^- \rightarrow Fe_2O_3 + H_2O + H_{2(g)}$$

   The result is formation of hematite and the production of hydrogen gas.

An important conclusion to this sequence is that the weathering of kimberlite in low-temperature surficial environments will produce hyperalkaline and extremely reducing groundwater. Partly with these concepts in mind, a study was initiated over several kimberlites deeply covered by glacial overburden. The purpose of the study was to determine 1) the chemistry of groundwater in the kimberlite; 2) the partial extraction geochemical response of the kimberlite in shallow surface soils; and 3) the pH, redox and electrical field response, if any, on surface. Five kimberlites were sampled for groundwater over a 5 week period by personnel from the University of Texas at Dallas. The kimberlites sampled were B-30, C-14, Diamond Lake and A4 in the Kirkland Lake area and 95-2 near New Liskeard (*see* Figure 27.1). Field measurements showed that the groundwater in the kimberlites are indeed hyperalkaline and reducing, with pH values as high as 12.00 and Eh that are, in some cases, below –500 SHE. No analytical data are available yet, but an orientation survey by the OGS, several years ago at some of the same kimberlites, showed unique groundwater chemistry. These data provide good justification for carrying out surface geochemical and electrogeochemical surveys to determine if this groundwater response has a surface expression.

While groundwater sampling was taking place, surface soils were collected at B-30, C-14 and A4 by the GSC team members with help from the OGS. They were sampled using a depth-based protocol that collected the interval between 10 and 20 cm below the base of the A_0 soil horizon (i.e., the base of the leaf litter, twigs, etc.), which resulted in variable soil media being sampled. Subsamples were collected for the measurement of pH and ORP in the lab, from which air was excluded prior to freezing. The samples will remain frozen until shortly before analysis. ORP and pH results for B-30 are complete and are shown on Figure 27.12a. They show symmetrical lows in ORP within the surface trace of the kimberlite. The pH shows a weak, but consistent, high over the core of the kimberlite. Surprisingly, the media type, as indicated by different symbols on the figure, does not have a significant impact on either the pH or redox.

The electrical field and total field response in shallow peat and/or soils over the kimberlite were measured by the OGS team members. Electrical field was measured using standard spontaneous potential (SP) equipment, which included Cu-$CuSO_4$ half-cell type pots, a long reel of wire and a voltage datalogger. One of the pots was left at the base station, while the other was advanced along a transect crossing the kimberlite with the voltage between the 2 being continuously recorded at each station. Total field was measured similarly, but the mobile electrode was made of platinum (PtSP). This technique was developed by the OGS over the last 4 years. Timm and Moller (2001) used similar techniques and demonstrated that the total field is the sum of the electrical field voltage and the electrochemical (redox) field voltages.

In theory, there should not be a strong electrical field associated with a kimberlite because it is not a conductor, but there should be a very strong redox field. Figure 27.12b shows the electrical field and redox field (resolved by subtracting the SP data from the PtSP data) for the B-30 kimberlite . These plots show an insignificant electrical field, but a strong redox field response that corresponds reasonably well with the redox response by measurement of soil samples. The PtSP method is perhaps a better technique for measuring redox over large distances because it is faster and involves an *in situ*, averaged measurement.

These data show that PtSP is potentially a valuable tool that could delineate strongly oxidizable buried features and identify redox boundaries where upward transported metals may be accumulating. It could, therefore, differentiate magnetic features that are reducing, such as kimberlite, from those that are not, such as magnetic granite. When used in conjunction with SP, it could also potentially differentiate conductive and oxidizable bodies (e.g., sulphides) from conductive and non-oxidizable bodies (e.g., graphitic units) from non-conductive, but oxidizable, bodies (e.g., kimberlite). However, the platinum spontaneous potential technique was developed to be used in fully saturated peaty-type terrain and is not likely to work well in dry sands. Since spontaneous potential does not work well in areas of highly variable moisture content, it may prove difficult, in many cases, to use the 2 techniques simultaneously.

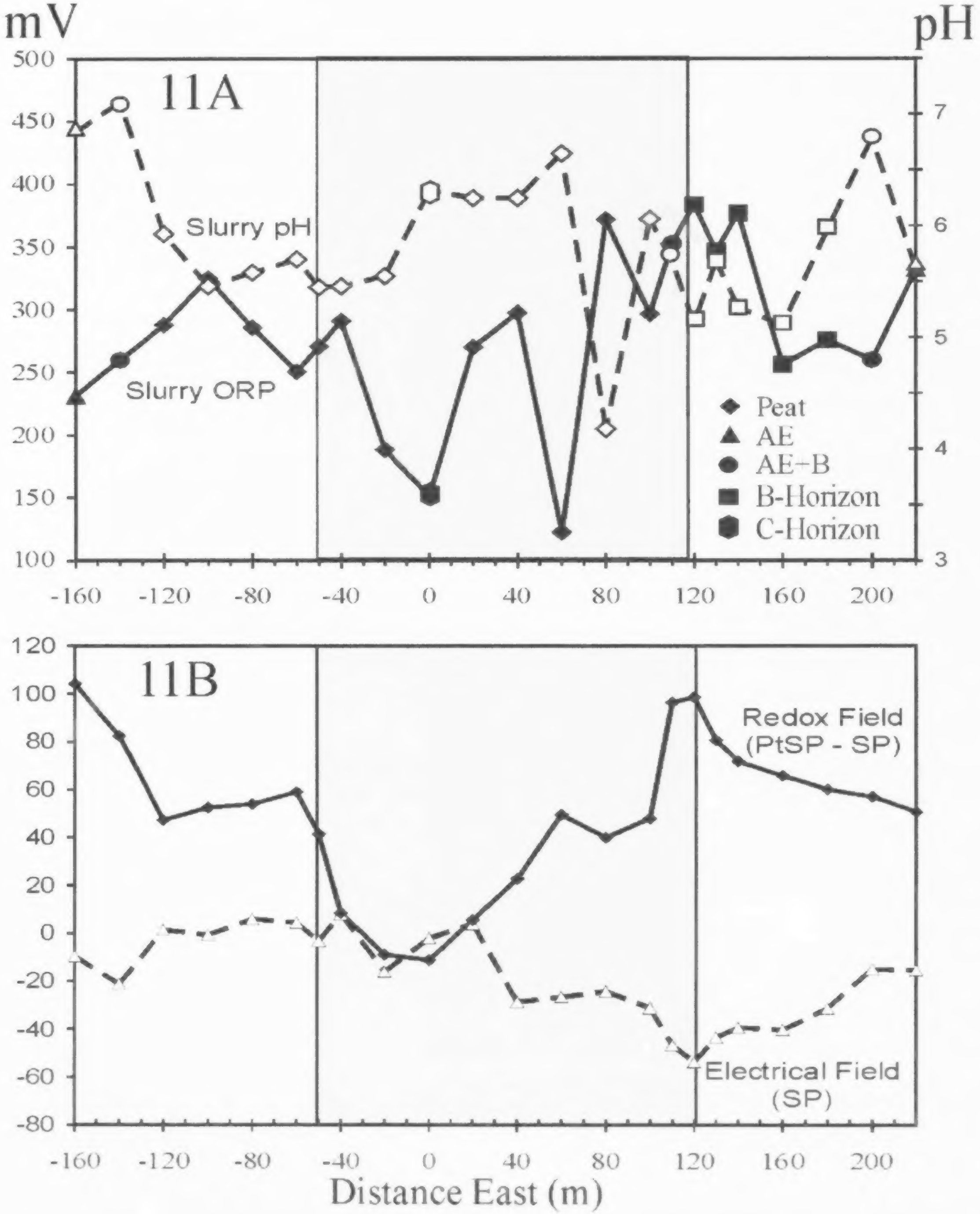


Figure 27.12. Oxidation-reduction potential (ORP), pH, spontaneous potential (SP) and platinum spontaneous potential (PtSP) over the B-30 kimberlite near Kirkland Lake. The shaded area indicates the extent of subcrop of the kimberlite. The B-30 kimberlite is covered by about 40 m of glacial sediment.

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28. Project Unit 02-017. Gold in Natural Waters: A Simple and Potentially Cost-Effective Exploration Method

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INTRODUCTION

Water as an exploration medium for gold has attracted some attention over the last 2 decades, primarily from government geological surveys and university researchers (e.g., Hamilton, Ellis, Florence and Fardy 1983; Hall, Vaive and Ballantyne 1986; Finch, Hall and McConnell 1992; Schmitt et al. 1993; Grimes et al. 1995). The mainstream exploration community has largely not embraced gold hydrogeochemistry, in part due to the time and expense of sample collection, complicated sample preparation and analysis that is required. The strategy behind most of the published methods for gold determination in waters (e.g., Brooks, Chatterjee and Ryan 1981; Hamilton, Ellis and Florence 1983; McHugh 1984; Hall, Vaive and Ballantyne 1986; Finch, Hall and McConnell 1991) require the collection of a large water sample (typically 1 L), and some combination of filtration, evaporation and addition of chemicals (e.g., HCl, HBr, MIBK) and/or activated carbon to capture any gold in solution or leach and capture gold that may have precipitated onto the walls of the sample container. Such methods, which are in essence a preconcentration, have been a necessity for several reasons, including 1) the inherent instability of gold in solution; 2) the fact that gold exists in natural waters at very low concentrations, typically less than 1 to 15 parts per trillion (ppt) (e.g., Hamilton, Ellis, Florence and Fardy 1983; Schmitt et al. 1993); and 3) the lack of sensitivity of analytical instrumentation for direct analysis. The strategy of the methodology described below is essentially the reverse of the traditional methods, that is, to allow and/or encourage the gold to precipitate out onto the walls of a plastic bag container, followed by analysis of the entire bag by instrumental neutron activation analysis (INAA) forgold. This method is still a form of preconcentration, but is low cost and simple, and is envisioned as a cost-effective exploration tool. An alternate methodology is on the horizon as well, which would involve direct analysis of water with no preconcentration, using new high resolution (HR) magnetic-sector inductively coupled plasma mass spectrometry (ICP–MS), with sensitivities below 1 ppt for many elements, including gold.

ADVANTAGES OF HYDROGEOCHEMISTRY

The advantages of hydrogeochemistry have long been known and are well summarized by various authors including Cameron, Marmont and Hall (1997), Hamilton, Ellis, Florence and Fardy (1983) and Schmitt et al. (1993). These advantages include

- The abundance of water bodies over the Canadian Shield;
- Relative ease of collection, whether by helicopter, boat or existing road networks;

Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.28-1 to 28-4.

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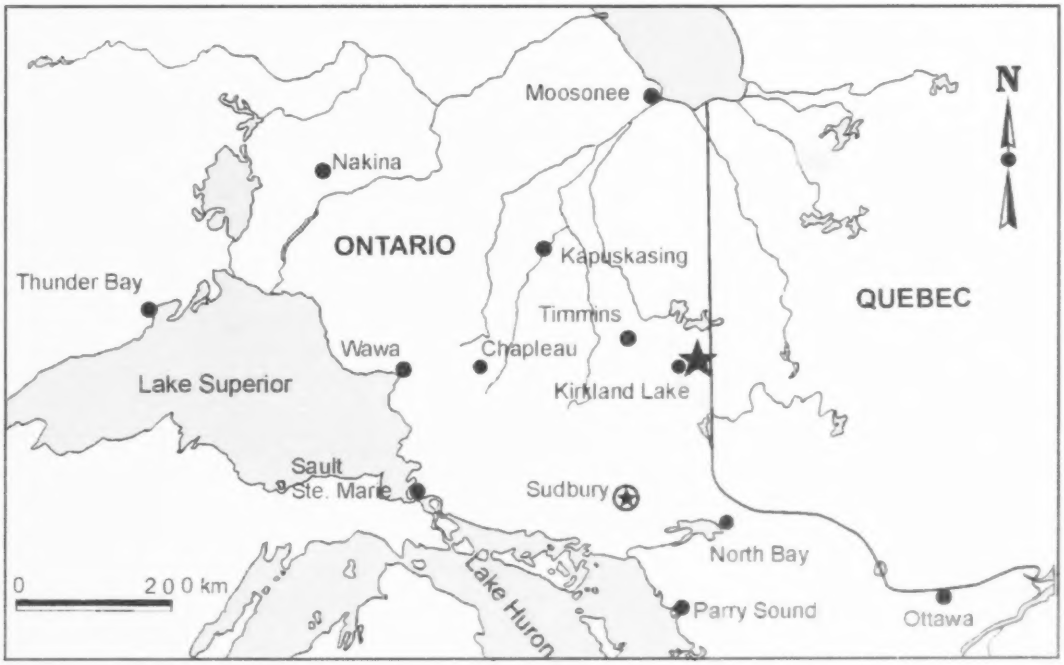
- Water is a homogeneous medium, much more so than most solid media, therefore, a single water sample can be representative of an entire water body, whereas one rock or basal till sample will rarely be representative of the surrounding geology;
- A single water sample may reflect the composition of a large volume of rock with which it has been in contact;
- Water samples from spring or groundwater fed lakes may reflect the metallic content of deeply buried rocks, which otherwise have no surface expression;
- Water can be analyzed directly (no sample preparation required) by ICP–MS for most trace elements of interest.

The successful application of hydrogeochemistry, including gold hydrogeochemistry, as a mineral exploration method has been demonstrated by a number of researchers (e.g., Lalonde 1983; Hamilton, Ellis, Florence and Fardy 1983; Schmitt et al. 1993; Grimes et al. 1995).

STUDY AREA

The Misema River – Misema Lake – Beaverhouse Lake water system near Kirkland Lake (Figure 28.1) was selected as the initial test area for this project. This area was chosen due to its location near existing gold showings, including the past-producing Upper Beaver Mine. The results of previous gold hydrogeochemical sampling done nearby at Victoria Creek (Hamilton et al. 1999) and closer to Kirkland Lake (Fortescue 1992) will be useful for comparative purposes.



N
Moosonee
Nakina
ONTARIO
Kapuskasing
Thunder Bay
QUEBEC
Timmins
Wawa
Chapleau
Lake Superior
Kirkland Lake
Sault Ste. Marie
Sudbury
North Bay
0
200 km
Lake Huron
Parry Sound
Ottawa

Figure 28.1. Location of the Beaverhouse Lake study area northeast of Kirkland Lake.

SAMPLING AND ANALYTICAL METHODOLOGY

The water sampling was done in conjunction with water limnological mapping being carried out by Aquapath Canada Ltd. Briefly, their methodology involves towing a Hydrolab® multi-parameter probe just above the floor of the lake. The Hydrolab® probe is attached to a sled, which also incorporates an underwater video camera and lighting. The "pilot" on the boat raises and lowers the sled as necessary to maintain a distance of 1 m above the lake bottom. The sensors on the Hydrolab® continuously log measurements of the bottom water, such as dissolved oxygen (DO), temperature, turbidity, pH, oxidation–reduction potential (ORP) and conductivity. Water sampling equipment consisted of a hose attached near the Hydrolab® connected to a pump onboard the boat. At each sample site, with the boat stationary, the pump/hose apparatus was allowed to purge for 3 minutes prior to sampling. A 50 mL syringe was filled approximately 6 times in order to filter a volume of 200 mL of water into a plastic baby bottle liner (for gold analysis) and 60 mL into a clean Nalgene™ high density polypropylene bottle (for direct ICP–MS analysis). Usually only one Millipore 0.45 μm Sterivex™ filter capsule was required per sample station. At several sites, an additional 200 mL filtered sample was collected as a field duplicate. At 10 sites, an additional 200 mL unfiltered sample was collected in a plastic bottle liner. The plastic bottle liner was always filled to the 200 mL line and immediately sealed with a handheld plastic sealing device. The 60 mL sample was kept cool and acidified with ultrapure nitric acid to a pH of less than 2 within 12 hours of collection. Water samples were collected both above and below the thermocline, at depths between 1.5 and 24 m. A total of 65 plastic bag samples were collected for gold analysis from 43 different sites.

Five days after collection, the plastic bags of water were opened and placed into an oven at 50°C in order to evaporate all standing water. For quality control (QC) purposes, several identical plastic bags, empty as well as filled with 200 mL of distilled water, were sequenced among the samples. The use of a microwave oven to quickly boil off the standing water may be a viable alternative; this will also be investigated.

The dry plastic bags will be rolled up, placed in irradiation vials and analyzed by INAA, principally for Au. Because this method is essentially a preconcentration (starting volume of 200 ml of water), the effective detection limit is 1 ppt.

DISCUSSION

Comparison of INAA gold data from filtered samples and unfiltered samples, in addition to data from direct HR magnetic sector ICP–MS of filtered and acidified samples, should allow conclusions to be drawn with regard to the necessity for filtering the water prior to sampling. This is seen as a fairly major impediment in terms of time and cost for the average explorationist. Over shield terrain, typically of shallow relief and poorly drained, the abundance of dissolved and colloidal gold (<0.45 μm Au) may be significantly higher than that for particulate gold. Schmitt et al. (1993), in studying several shield lakes, came to this general conclusion. Studies, such as by Hamilton, Ellis, Florence and Fardy (1983), whom sampled numerous stream waters for gold, have determined that particulate gold was quite varied and often abundant, depending on the level of suspended solids (e.g., clays) in the waters.

Ultimately, the goal of this project is to determine if gold hydrogeochemistry is a viable and cost-effective exploration method for the Ontario explorationist on the Canadian Shield. While the methodology described above may still seem cumbersome, the primary focus of this study is to determine a simple alternative to the methods that have been prevalent in the past. The ideal methodology can be summarized as follows:

1. collection of 200 mL of unfiltered water in a plastic bag (filtration likely necessary for stream waters)
2. evaporation of all water, either with heat oven (~50°C) or by microwave oven
3. analysis by INAA for Au

An alternative method that will be investigated is the use of direct HR magnetic-sector ICP–MS analysis of waters. Although the sensitivity of this method (sub-ppt) sounds promising, some method of either stabilizing the dissolved gold or leaching off any gold adsorbed to the container walls would be required. This would increase the complexity and cost compared to the INAA method described above, but would not require any preconcentration, therefore, a relatively small sample size of 60 mL would be sufficient.

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29. Project Unit 01-013. A Seamless Quaternary Geology Map of Southern Ontario: Second Phase

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INTRODUCTION

In response to increased demand for readily accessible and easily understood information on the surficial sediments of southern Ontario, the Ontario Geological Survey (OGS) has undertaken an initiative to generate a seamless map of the Quaternary geology for the region. The region is covered by about 120 Quaternary geology maps (*see also* Bajc et al. 2001, Figure 33.1). The final product resulting from this project will form an information layer in the Land Information Ontario (LIO) warehouse. Initial funding for the project was supplied by the Water Resources Inventory Program of the Ministry of the Natural Resources (MNR) and is currently supported by the Ministry of Northern Development and Mines groundwater program.

The initial phase of work on the project included data automation, data quality checks and translation of the attribute tables to a provincial standard (Bajc et al. 2001). A set of digitized maps tied to a common legend has been generated for southern Ontario.

In the summer of 2002, field work was conducted to resolve the problems of boundary faults and unlabelled geological entities between and among maps. Concurrent with this, map editing to standardize landform data and correct displacement (e.g., overlaps caused during the digitizing process) continued in the office. The following description is focussed on the field work component of the project.

FIELD WORK

Field work was conducted in the areas across southern Ontario where boundary faults existed between published maps, and unlabelled map polygons were identified during the phase 1 work. Field work focussed on correcting map problems in areas accessible by road. Areas represented by small polygons beyond road access in remote areas are being assessed using aerial photographs, digital elevation models (DEM) and topographic maps as well as geological sedimentary models. These methods allow the problems to be corrected and provide an estimation of deposit type.

Using a global positioning system (GPS) connected to a laptop computer installed with ArcView® and Geographic Tracker® AVX, desired localities were located and co-ordinates were obtained for field stations. Two types of data were collected in the field and provide the primary means to correct boundary faults and identify unlabelled polygons.

The first data set involved logging sections and examining outcrops at man-made and natural exposures, sand and gravel pits, as well as drilling shallow (1.2 m) boreholes using a Dutch hand auger.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.29-1 to 29-2.

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In addition to the sediment data, landscape information in the surrounding area was also recorded. In total, about 500 stations were recorded. A digital spreadsheet has been created for the field data, which may be viewed, in the future, as a GIS theme.

The second data set involved obtaining general field observations, when traversing Precambrian or Paleozoic bedrock terrain. The location of Precambrian and Paleozoic outcrop is required for boundary corrections in areas mapped as bedrock or bedrock drift. For these outcrop locations, UTM co-ordinates were not collected in the field. Although less accurate, the co-ordinates will be generated by measuring the localities on the maps in the office.

The sediment type that exists at a depth of 1 m below the surface is regarded as the mappable material, that is, the units must be at least a 1 m thick to be represented on the map. For instance, thin sand often overlies the marine silt and clay in the eastern part of the Champlain Sea basin. However, since the sand is less than 1 m thick, the underlying silt and clay is regarded as the geological unit to be mapped.

FUTURE WORK AND TIME TABLE

The surficial maps will be standardized during the winter of 2002 and spring of 2003. The field data will be interpreted and used to correct map boundaries and label unidentified polygons. Apart from the field data, supplementary data will be required primarily from

- aerial photographs for the areas inaccessible by roads;
- water well records, which provide information on drift thickness and may be useful in dealing with the areas mapped as bedrock or bedrock with thin drift;
- published and unpublished geological reports and papers, such as OGS aggregate resources inventory maps;
- bedrock geology maps, which will be used for areas where no differentiation has been made between Precambrian and Paleozoic bedrock;
- sand and gravel pit records kept by the Ministry of Transportation (MTO).

As time and resources allow, work will be undertaken on refining map attribute data and the provincial standard legend. Co-operation with MNR staff will continue to improve and streamline the proposed data model to ensure both map query efficiency and quality (data standards and LIO warehouse requirements: J. Ernsting and B. Hayes, Ministry of Natural Resources, written communications, 2002).

The finished seamless surficial maps, without boundary faults, are expected to be available to the public in the spring of 2003.

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30. Project Unit 02-019. Groundwater Resource Inventory Papers (GRIPs)

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INTRODUCTION

Under the province's Clean Water Strategy, the Sedimentary Geoscience Section (SGS) of the Ontario Geological Survey (OGS), Ministry of Northern Development and Mines (MNDM) has established a program of groundwater mapping. The main objectives of the program are to "map out" the location of major groundwater aquifers across southern Ontario and selected regions of northern Ontario and to provide information on their physical characteristics. As well, information regarding the susceptibility of aquifers to contamination will be generated. The information will support decision makers in developing future resource management policy and will support the development of local and regional groundwater protection strategies.

Currently, the groundwater-mapping program has 4 main components or initiatives. These include 1) the generation of a "seamless", geographic information system (GIS) based map of the surficial geology for southern Ontario; 2) initiation of a three-dimensional geological mapping pilot project, for example, Waterloo Moraine in southwestern Ontario; 3) data management and modelling for collected information; and 4) generation of groundwater resource inventory papers or GRIPs. The latter initiative will be discussed within this article as the former 3 are discussed elsewhere in this volume.

BACKGROUND

As part of an integrated program submission, within the 2001–2002 fiscal year, the ministries of Northern Development and Mines, Natural Resources, Environment, and Agriculture and Food proposed a multi-year strategy to address the issues facing drinking water in Ontario. In July of 2001, MNDM received funding to undertake the initial phase of an "Aquifer Mapping and Susceptibility to Contamination" program. This program was part of a larger funding envelope to the 4 ministries mentioned above. For fiscal year 2002–2003, additional funding was approved to continue the MNDM's aquifer mapping program.

MNDM's program, delivered through the OGS, contributes to the 4 pillars of the Clean Water Strategy, namely, groundwater information, source protection, managing water taking, and reducing risks.

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GROUNDWATER RESOURCE INVENTORY PAPERS

As mentioned above, the aquifer-mapping program currently has 4 main components or project areas of which the Groundwater Resource Inventory Papers is one.

In watersheds, groundwater forms an integral component of the hydrological environment. For instance, groundwater provides baseflow to many parts of a watershed and, thereby, supports that watershed's aquatic ecosystems. In other cases, groundwater may provide the main source of drinking water for many residents or may provide critical water supplies to industrial and commercial operations.

In many parts of Ontario, it is recognized that the level of mapping and information available to understand groundwater flow conditions across watersheds is inadequate to allow informed land-use decisions to be made.

In order to provide the basic geologic and hydrogeologic information needed to address the hydrogeological regime(s) present in watersheds, the OGS has initiated development of a series of reports known as Groundwater Resource Information Papers (GRIPs). The goal of these reports is to provide a series of regional-scale interpretive maps, information and data that can be used to better understand the groundwater system(s) present in individual watersheds.

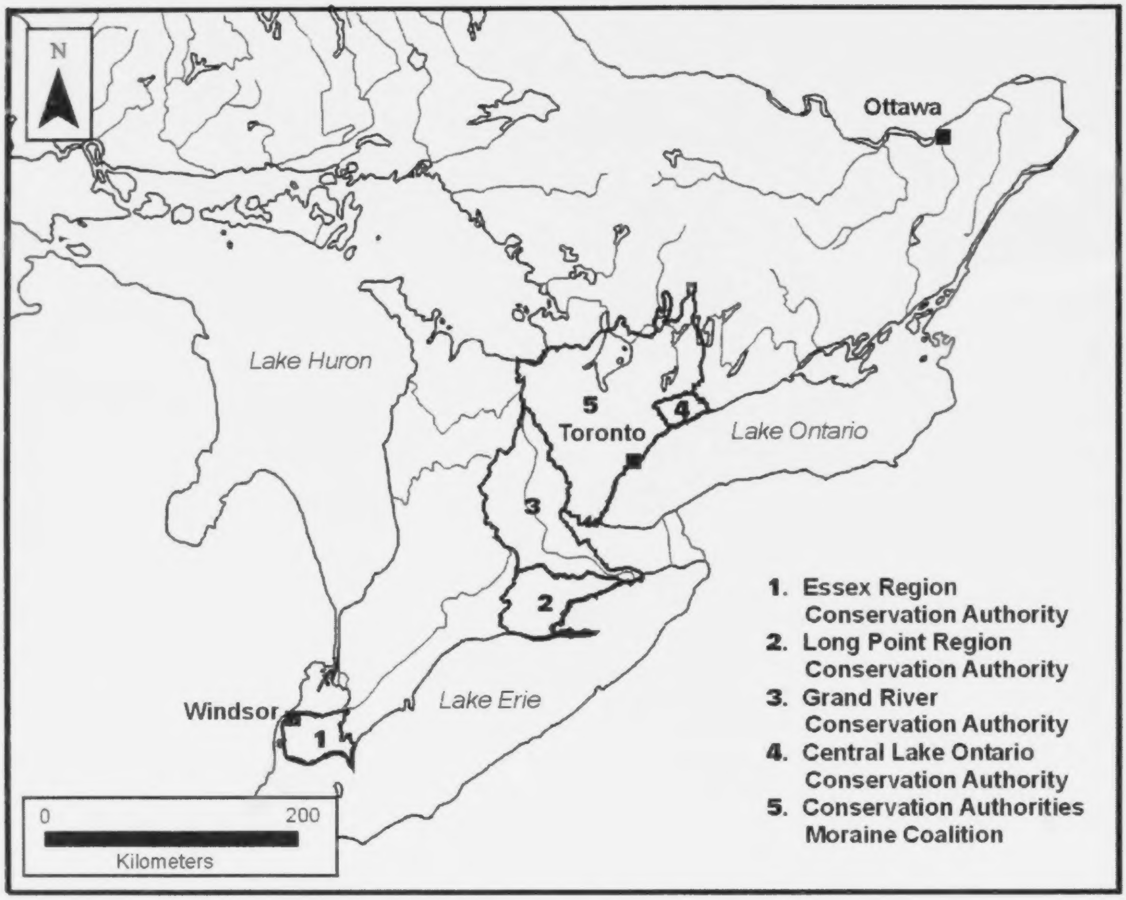
It should be noted that some jurisdictions have undertaken the development of studies similar in scope to GRIPs, for example, the Grand River Conservation Authority (2001) or the municipal groundwater studies currently being funded by the Ontario Ministry of the Environment. The intent of GRIPs is not to replicate the work of these initiatives, but to build upon them and, where feasible, incorporate existing, valuable geoscience data layers.

By completing a series of comprehensive, similarly structured groundwater inventory reports, ready comparison of groundwater systems between watersheds and regions will be possible. As well, the geoscience information generated by the studies will form the framework upon which three-dimensional mapping of aquifers will be constructed.

To date, partnership arrangements have been formed with 4 conservation authorities (CA) to complete GRIPs (Figure 30.1). These are

- Grand River
- Central Lake Ontario
- Essex Region
- Long Point Region

Arrangements for the completion of GRIPs in conjunction with the Conservation Authorities Moraine Coalition (CAs covering the Oak Ridges Moraine area) (*see* Figure 30.1) are being finalized. Discussions with other conservation authorities to complete GRIPs are also underway. It is hoped that with continued funding groundwater resource inventory papers will be completed for all of the major watersheds across southern Ontario and selected locations in northern Ontario over the next few years.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1. Essex Region Conservation Authority
2. Long Point Region Conservation Authority
3. Grand River Conservation Authority
4. Central Lake Ontario Conservation Authority
5. Conservation Authorities Moraine Coalition

Figure 30.1. Location of conservation authorities (1 to 4) for which groundwater inventories are currently being completed and location of ones currently being initiated (5).

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31. Project Unit 02-018. Mapping the Subsurface of Waterloo Region, Southwestern Ontario

A.F. Bajc

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BACKGROUND

Pressures directed at protecting and preserving the quality and sustainability of groundwater resources within the province have greatly increased over the past decade. For example, the impacts of rapid urban expansion from metropolitan centres and nutrient management practices in rural areas must now be considered when assessing the long-term preservation of groundwater. Wise land-use planning is essential, especially within recharge areas where aquifers are replenished and are most susceptible to contamination. A detailed understanding of the properties and three-dimensional architecture of Quaternary deposits is essential if well-informed decisions regarding land use are to be made.

As a significant start to this process, the federal and provincial geological surveys have co-operatively undertaken an extensive program of Quaternary geology, hydrogeology and database management within the Oak Ridges Moraine (ORM) of south-central Ontario (Sharpe, Hinton and Desbarats 2002). The ORM is a provincially significant geological feature located north of the Lake Ontario shoreline. Sensitivities over land use are paramount within this area of rapid urban expansion. Details of this multidisciplinary geoscience program can be found at http://sts.gsc.nrcan.gc.ca/orm/index.asp. Future studies within other areas of the province should attempt to follow an approach similar to that developed for the ORM.

The Sedimentary Geoscience Section of the Ontario Geological Survey (OGS) is embarking on a new program as part of a provincially mandated directive to study groundwater resources within the province. Several projects are being undertaken as part of this program. These include 1) the generation of a seamless, 1:50 000 scale, attributed Quaternary geology map of southern Ontario (Bajc et al. 2001); 2) the development of data model standards for three-dimensional mapping and hydrogeological investigations (van Haaften, this volume); 3) the assemblage and filtering of subsurface information (mainly water well data from the Ontario Ministry of the Environment and Energy (MOEE)) by selected Conservation Authorities in southern Ontario following the methods employed by the Grand River Conservation Authority (GRCA) in their three-dimensional studies (Holysh, Pitcher and Boyd 2001); and 4) the generation of a three-dimensional model of Quaternary geology within the Regional Municipality of Waterloo (RMOW). This article summarizes the current status of three-dimensional studies within the RMOW. The project is being undertaken in co-operation with the RMOW and the GRCA.

The RMOW is the largest municipal user of groundwater in Canada. Its average daily production exceeds 160 000 m^3 supplying water to about 395 000 residents (Robinson 2001). The region is centrally located in the interlake area of southwestern Ontario (Figure 31.1) and occupies an area of approximately 1400 km^2. Lying within the region is the Waterloo Moraine, an interlobate feature composed of interbedded sand and gravel. Deposits of the Waterloo Moraine house the aquifers that store a significant proportion of the water extracted for municipal use within the region.

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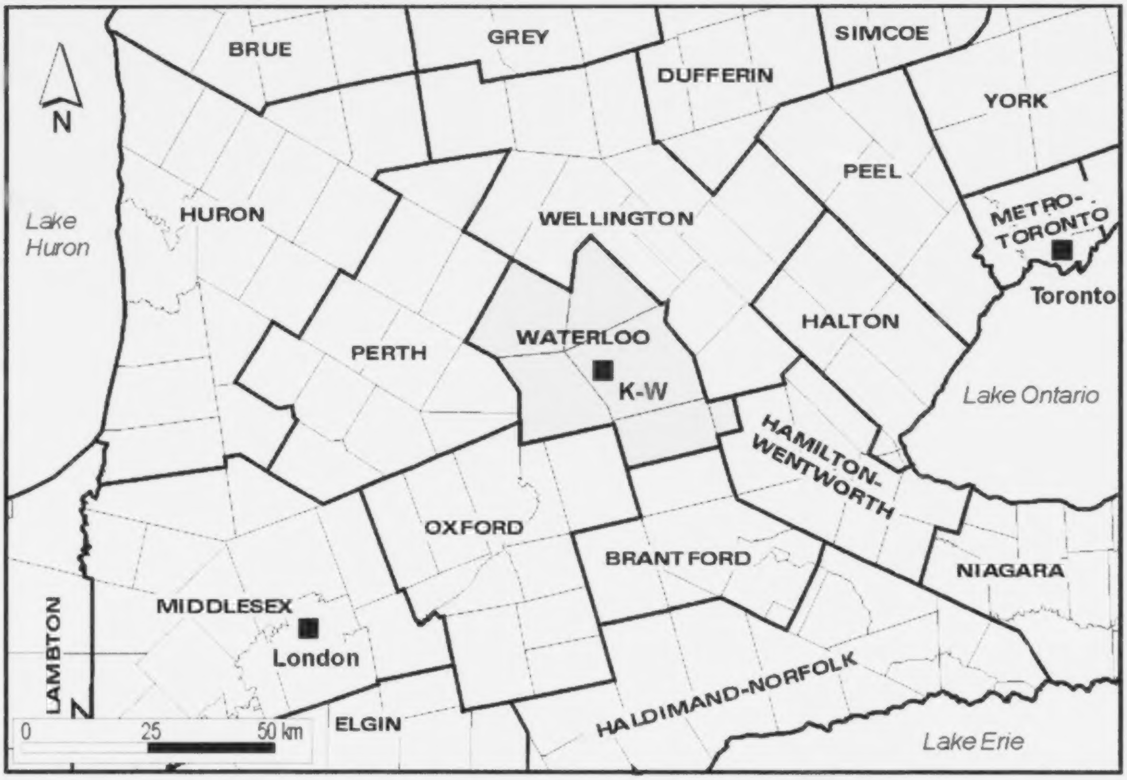
The RMOW is one of the most advanced municipal governments in Ontario in terms of its hydrogeological monitoring programs. It utilizes more than 130 dedicated observation wells to record water levels, monitor water quality and measure aquifer pressures on a regular basis (Robinson 2001). The RMOW is also fortunate in that both the University of Waterloo Ground Water Research Institute, a world-class hydrogeology department and the Quaternary Sciences Institute, are situated within the region. The GRCA is also very active in both surface and subsurface water monitoring programs. Numerous studies, dealing with Quaternary stratigraphy, sedimentology and groundwater modelling have been undertaken within the RMOW. Most of these have been undertaken by the staff and students of the University of Waterloo or consultants who obtained their training at the university. The GRCA has also produced a comprehensive technical report on the regional groundwater conditions within the Grand River watershed (Holysh, Pitcher and Boyd 2001).

OBJECTIVES AND WORK PLAN

The main objective of this project is to generate a three-dimensional geologic model of the Quaternary geology of the RMOW to assist with hydrogeologic modelling. Quaternary studies over the last 4 decades have already resulted in a fairly good understanding of the Late Wisconsinan stratigraphic record of the region. Most studies, however, focussed on till stratigraphy with little detail directed to the intertill stratified drift. Facies modelling of these deposits will be undertaken to bolster the geological model already in place. As well, the record of pre-Late Wisconsinan deposits is fragmentary and requires further study.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PEEL
METRO-TORONTO
Toronto
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WELLINGTON
HALTON
WATERLOO
K-W
PERTH
Lake Ontario
HAMILTON-WENTWORTH
OXFORD
BRANTFORD
NIAGARA
MIDDLESEX
London
LAMBTON
HALDIMAND-NORFOLK
ELGIN
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25
50 km
Lake Erie

Figure 31.1. Location of the Regional Municipality of Waterloo in southwestern Ontario.

The development of a three-dimensional geologic model requires a strong understanding of the Quaternary geology. To this end, the author spent 8 weeks in the field during the summer of 2002 observing landscapes, classifying terrain, examining existing natural and man-made exposures and undertaking detailed sedimentological studies of stratified deposits exposed mainly in licensed sand and gravel pits. Several cores recently drilled for the RMOW were also logged in detail to become familiar with the deposits of the Waterloo Moraine and some of the older stratigraphic units.

The second phase of this project will involve the compilation and examination of as many data sets as possible that record subsurface geology within the region. The highest quality data sets reside at the RMOW and the University of Waterloo Department of Earth Sciences. Numerous studies that required continuous coring of the overburden have been undertaken by both the region and the university. These records will be studied in detail and will form the basis of the derived three-dimensional geologic model. Abundant subsurface information is also stored within a geotechnical database created by the Geological Survey of Canada (GSC) during the early 1970s. This database is somewhat dated and requires updating. As well, geotechnical records are contained within the files of the region's engineering department and with private consulting firms. Additional information is also contained within field notes of Dr. P.F. Karrow who mapped the Quaternary geology of the Stratford–Conestogo areas for the GSC and the Cambridge and Guelph areas for the OGS. Most of this information will, however, address the near-surface stratigraphy of the region. The MOEE water well database will also be used to produce derived bedrock topography and drift thickness maps.

All of these data sets will be stored within a database with a structure following that proposed by the OGS as part of its data modelling exercise (van Haaften, this volume). Preliminary interpretations of these data will be undertaken using three-dimensional viewing software such as ViewLog®, Rockworks®, GoCAD® and Surfer®. Following this initial interpretation, additional geological information will be obtained to address gaps in the data sets as well as to assist with the geological modelling exercise. Geophysical surveys, including ground penetrating radar (GPR) and shallow seismic reflection will be undertaken in areas of poor exposure and areas where suspected buried bedrock valleys occur. Additional continuous coring of the overburden to bedrock will be undertaken to fill-in gaps, address geological problems and target potential older stratigraphic records in buried bedrock valleys.

The final phase of the geological modelling exercise will involve the analysis of the existing water well database to determine whether it can be trained to yield useful information on the subsurface stratigraphy of the region. A similar exercise was undertaken by the GSC in the Oak Ridges Moraine data set with mixed results (Russell et al. 1998). Most problems arise from the over-representation of clay in the stratigraphic sequence and the inability to distinguish between sand and gravel and coarse-grained till.

REGIONAL GEOLOGIC SETTING

Bedrock outcrops are uncommon within the RMOW. The position of bedrock formational contacts is inferred from irregularly spaced boreholes that penetrate the bedrock surface. The region is underlain by late Silurian age dolostones of the Guelph Formation and interbedded green to grey shales and dolostones of the Salina Formation. The approximate contact between the 2 formations passes under the cities of Kitchener–Waterloo just west of the Grand River. Thin- to medium-bedded dolostones of the Bass Island Formation subcrop in the extreme northwestern corner of the region in Wellesley Township.

Drift thickness within the RMOW is highly varied. Depths frequently exceed 30 m and occasionally surpass 100 m, especially within the Waterloo Moraine. The bedrock surface slopes gently from an elevation of approximately 350 m asl in the northwest to 225 m asl in the southeast. The extension of the Dundas buried valley and its tributaries into the region likely accounts for added bedrock relief.

Although the record of Late Wisconsinan glaciation within the RMOW is relatively well understood, the record of older glacial and non-glacial events is fragmentary. Many publications summarizing the current status of knowledge of the Quaternary stratigraphy have been published over the past 4 decades. Most references pertinent to this study can be found in the citations following a paper by White and Karrow (1996) on the urban and engineering geology of the Kitchener–Waterloo area as well as within a recent paper on the origin of the Waterloo kame moraine (Karrow and Paloschi 1996).

The Quaternary record preserved within the RMOW is characterized by repeated glacial advances of ice lobes originating from the Huron–Georgian Bay and the Erie–Ontario lake basins. Indicator clast lithologies assist with determining provenance. For example, till originating from the Huron-Georgian Bay lobe often contain clasts of Proterozoic-age metasedimentary rocks, including jasper conglomerate, Gowganda Formation tillite and quartzites. Erie–Ontario lobe tills often contain mottled red and green Queenston Formation shales and red to white sandstones and siltstones. Grenville marble is occasionally encountered as well in Erie–Ontario lobe deposits.

Pre-Late Wisconsinan drift has been encountered at numerous locations within the RMOW. It consists of a complex sequence of older, fine- and coarse-textured tills and stratified deposits. The Canning Till, a fine-textured till displaying a reddish colour is the only formally named pre-Late Wisconsinan till unit recognized within the RMOW. The reddish colour of this till is likely derived from Queenston Formation red shales that outcrop below the Niagara Escarpment to the east. An Erie–Ontario source lobe is suggested (White and Karrow 1996). Alluvial channel-fill deposits containing organic remains have been encountered at a few sites. The Waterloo interstadial site has an age of 40 ka BP and represents the deposits of a Middle Wisconsinan nonglacial episode (Karrow and Warner 1984).

The main Late Wisconsinan glaciation is represented by the Catfish Creek Till. This silty to sandy till of northern provenance is often overconsolidated and forms an important marker horizon within the region (Karrow 1988). It occurs frequently in borings, roadcuts and sand and gravel pit and river bank exposures. Following a significant retreat of ice from southwestern Ontario (Erie Interstade), competing lobes of Huron–Georgian Bay and Erie–Ontario ice advanced into the region. The sequence and age relationships of the till sheets identified to date are highlighted in Figure 31.2. Significant moraines are associated with some of the till sheets. For example, the Macton Moraine represents the outer limit of the Mornington Till and the Paris Moraine represent the outer limit of the Wentworth Till. The Waterloo Moraine was constructed during the ice advance that deposited the Maryhill Till.

THE WATERLOO MORAINE

The Waterloo Moraine is defined as an irregular tract of gently rolling to hummocky terrain occupying an area of approximately 500 km^2. It lies west of the Grand River between Hawkesville in the north and New Dundee in the south and extends westward to Phillipsburg. Distinct spurs of sand and gravel extend outward from the moraine to the north, west and south. The relationship of these spurs to the Waterloo Moraine is under investigation. The vast accumulations of sand and gravel comprising the Waterloo Moraine are sometimes blanketed by clayey Maryhill Till or sandy Port Stanley Till. The moraine is believed to be the product of the ice advance that deposited the Maryhill Till (Karrow and Paloschi 1996). This clay-rich till, which is often interbedded with glaciolacustrine deposits, occurs as layers at the base, within and above the morainic deposits. The layers are discontinuous in all 3 environments.

All of the sand and gravel deposits comprising the moraine have been mapped as ice-contact stratified drift. This classification is likely based solely on geomorphology since there are very few exposures within the moraine proper. The stratified deposits comprising the Waterloo Moraine are an important aquifer for the RMOW. A better understanding of the depositional environments into which these sands and gravels were deposited is essential to better predict where the greatest potential for additional groundwater reserves exist.

NEW FINDINGS

Several new observations were recorded as part of the field work that will assist with the development of the geological model. The Waterloo Moraine has been described as a hummocky to rolling tract of land. Some of the hummocky terrain is, in fact, interpreted as erosional or dissected in origin. Dissection likely occurred during and shortly following retreat of the Erie–Ontario lobe from the region as glacial lakes drained and base levels fell. Surface morphology throughout the region should be classified to assist with the determination of facies models. Few exposures within the moraine actually display ice-contact features such as faults and chaotic bedding. The moraine appears to be composed of a complex network of subaquatic fan, deltaic, braided stream, subglacial conduit and kame and/or kettle depositional environments. The youngest morainic sediments were likely deposited within a transitional basinal to shallow lacustrine environment. In fact, the glaciolacustrine environment appears to dominate most of the deposits observed in sand and gravel pit exposures. Coarsening upward sequences indicate basin filling or shallowing processes late in the development of the moraine. Most paleocurrents obtained from planar cross-beds, trough cross-beds and steeply dipping foreset beds within the moraine indicate paleoflow towards the west to northwest. This is consistent with an Erie–Ontario source lobe for the moraine.

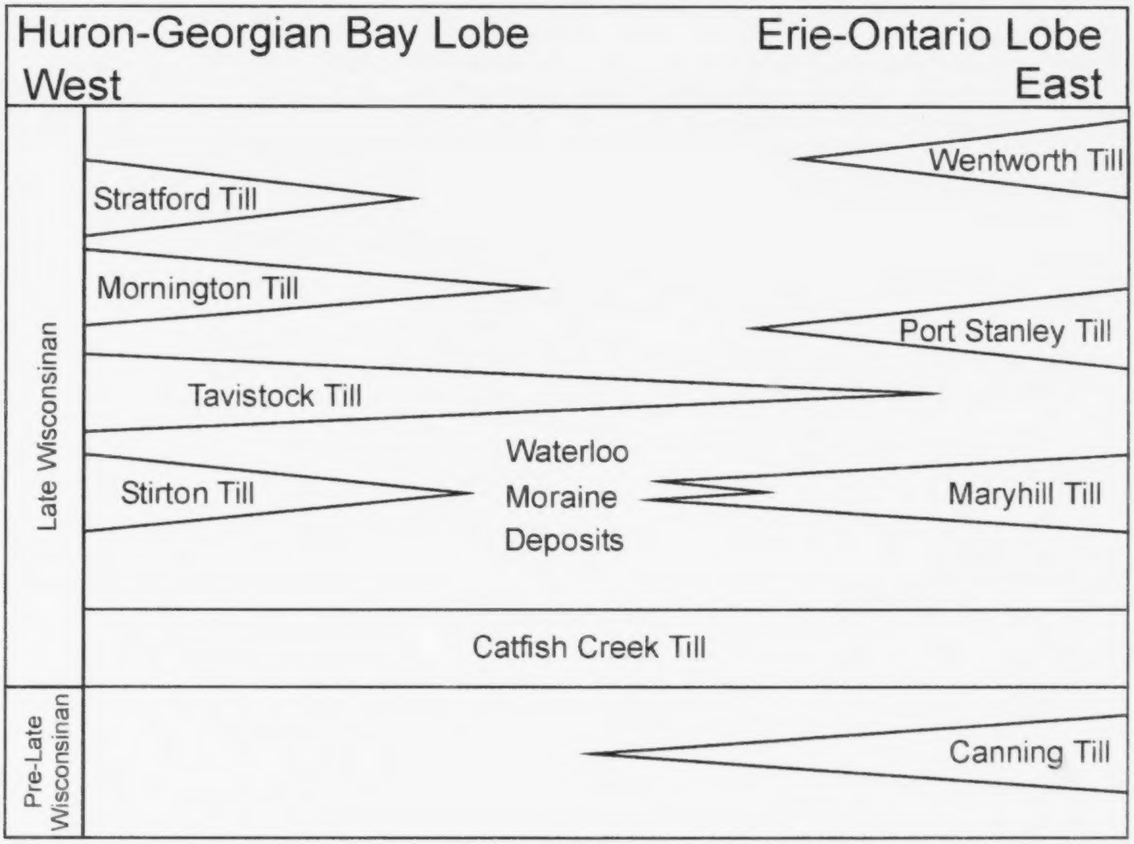
Huron-Georgian Bay Lobe
West
Erie-Ontario Lobe
East
Wentworth Till
Stratford Till
Mornington Till
Port Stanley Till
Tavistock Till
Waterloo
Moraine
Deposits
Stirton Till
Maryhill Till
Catfish Creek Till
Canning Till
Late Wisconsinan
Pre-Late Wisconsinan

Figure 31.2. Generalized till stratigraphy within the Regional Municipality of Waterloo (*adapted from* Karrow and Paloschi 1996).

Aside from general statements describing coarsening upward sequences, few descriptions are available on the nature of the morainic deposits at depth. Existing borehole logs will be studied to determine the nature of the lower morainic deposits. Future searches for substantial groundwater resources within the morainic deposits should be focussed on depressions in the upper surface of the Catfish Creek Till where subglacial meltwaters associated with the advancing Maryhill ice would be directed. One might expect linear bodies of coarse-grained conduit deposits with high permeability and hydraulic conductivity within these depressions.

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32. Project Unit 02-024. Data Modelling for Aquifer Mapping

S. van Haaften

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INTRODUCTION

Aquifer mapping seeks to map the surface and subsurface geology of a study area in 2 and 3 dimensions. It also seeks to map the occurrence of groundwater within the ground, and its relationships with the geology. This will provide a sound geological and hydrogeological basis for determining groundwater availability, and susceptibility to contamination.

The Ontario Ministry of Northern Development and Mines (MNDM), Sedimentary Geoscience Section is undertaking a variety of aquifer-mapping projects. To ensure suitable data organization for doing the work and for data management, a data modelling project was undertaken for aquifer mapping and related data. Data models are representations of how data may be stored in a computer system, and they usually comprise data model diagrams with accompanying text. Data modelling results were synthesized in an unpublished Ontario Geological Survey report and this summary, providing a data management basis for MNDM's aquifer mapping programs.

MNDM has made efforts to achieve compatibility of its data models with other data models currently used in Ontario for groundwater–subsurface geology purposes. Groups actively working in the groundwater and subsurface geology fields were invited to help with the project. To date, the working group has had a full-day meeting and 2 teleconferences. Individual and group interviews were conducted with several groundwater workers, to obtain specific input for this project. The project also drew on MNDM's previous experience, including experience with water well and geotechnical borehole data.

Concurrently with MNDM's data modelling project, the Ministry of Natural Resources (MNR) initiated a data modelling study of three-dimensional data (Nestel 2002). An important objective of the MNR project was to define high-level data models for storing these data in central information systems. MNDM's data models should fit within the high-level data models recommended in the MNR study, for implementation on provincial servers.

AQUIFER MAPPING DATA AND DATA FLOW

Aquifer mapping requires bringing together and processing available data sets, as well as collecting new data. New data collection may include geological drilling to determine an area's stratigraphic framework, geological mapping and geophysical surveys to supplement available information, and groundwater monitoring. Incoming data for aquifer mapping are illustrated in Figure 32.1.

Summary of Field Work and Other Activities 2002.
Ontario Geological Survey, Open File Report 6100, p.32-1 to 32-9.

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From the incoming data, derived data are generated, such as

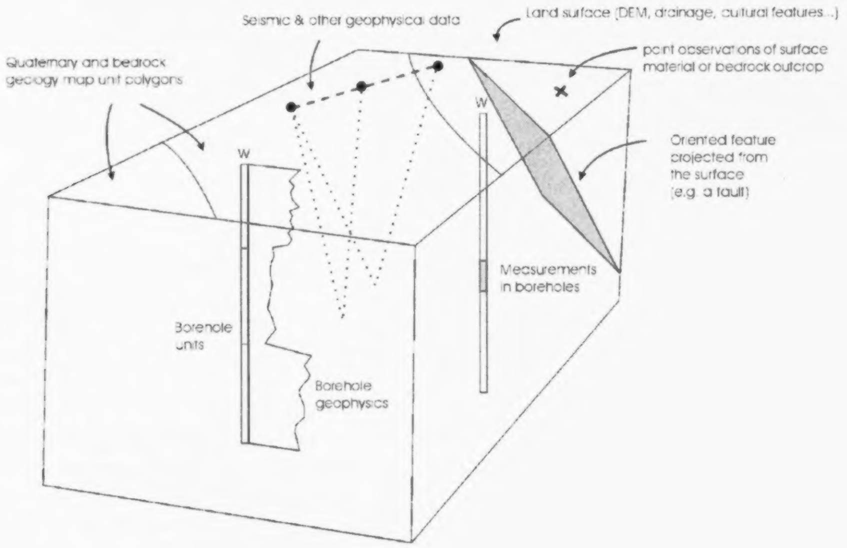
- stratigraphic "picks" for the tops and/or bottoms of specific formations in boreholes;
- interpolated surfaces of the top of the water table, of bedrock elevation, and of the tops and bottoms of specific formations, aquifers, and aquitards;
- the "shapes" and volumes of specific geological units and aquifers;
- groundwater flow data and models, generated in three-dimensional space;
- susceptibility (to pollution) maps;
- groundwater recharge and discharge areas.

Data Flow

Figure 32.2 shows the possible data flow within an aquifer-mapping project. Explanations of Figure 32.2 follow.

DATA ARCHIVE AND PROCESSING

Geologists need to obtain a variety of existing geological data, as noted above. The data will be imported to the project archive, and processing will occur within the archive. For example, borehole geology will be used to enhance geological maps, and the geological materials classification of geology maps will be used to reclassify descriptions of borehole strata, thus extending the on-surface geological classification into the subsurface. The data archive will be maintained in an organized manner using standard software.



Seismic & other geophysical data
Land surface (DEM, drainage, cultural features...)
Quaternary and bedrock geology map unit polygons
point observations of surface material or bedrock outcrop
W
W
Oriented feature projected from the surface (e.g. a fault)
Measurements in boreholes
Borehole units
Borehole geophysics

Figure 32.1. Sketch of aquifer-mapping incoming data sets.

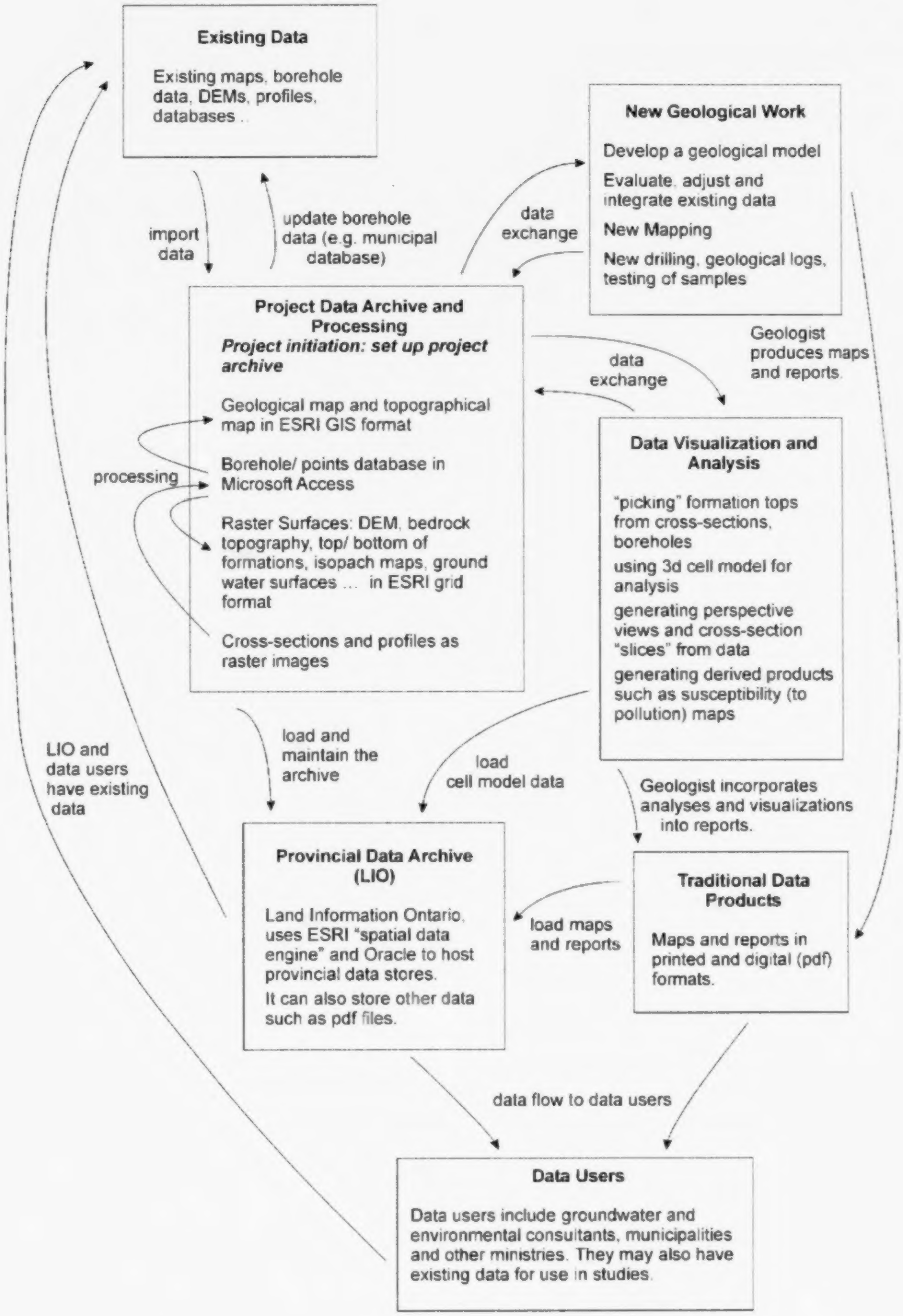

Existing Data
Existing maps, borehole data, DEMs, profiles, databases ..
New Geological Work
Develop a geological model
Evaluate, adjust and integrate existing data
New Mapping
New drilling, geological logs, testing of samples
import data
update borehole data (e.g. municipal database)
data exchange
Project Data Archive and Processing
Project initiation: set up project archive
Geological map and topographical map in ESRI GIS format
Borehole/ points database in Microsoft Access
Raster Surfaces: DEM, bedrock topography, top/ bottom of formations, isopach maps, ground water surfaces ... in ESRI grid format
Cross-sections and profiles as raster images
processing
data exchange
Geologist produces maps and reports.
Data Visualization and Analysis
"picking" formation tops from cross-sections, boreholes
using 3d cell model for analysis
generating perspective views and cross-section "slices" from data
generating derived products such as susceptibility (to pollution) maps
load and maintain the archive
load cell model data
Geologist incorporates analyses and visualizations into reports.
LIO and data users have existing data
Provincial Data Archive (LIO)
Land Information Ontario, uses ESRI "spatial data engine" and Oracle to host provincial data stores.
It can also store other data such as pdf files.
load maps and reports
Traditional Data Products
Maps and reports in printed and digital (pdf) formats.
data flow to data users
Data Users
Data users include groundwater and environmental consultants, municipalities and other ministries. They may also have existing data for use in studies.

Figure 32.2. Aquifer-mapping data flow diagram.

NEW GEOLOGICAL WORK

This part of Figure 32.2 recognizes the geologist's role in aquifer mapping. Geologists need to evaluate and integrate the existing surface and subsurface information. They need to develop a geological model to guide interpretations, and very likely they'll do field work, such as new mapping and logging of exposures, to supplement existing data. They may also drill new boreholes, log and sample the materials and possibly monitor groundwater conditions. Geophysical surveys and geophysical logging of boreholes may also be performed.

DATA VISUALIZATION AND ANALYSIS

Data visualization and analysis were placed in a separate box within Figure 32.2 because they may involve a wide variety of scientific data processing and analysis, not all of which will use the standard data organization and software of the project data archive. Specialized hydrogeological software, geostatistical software and data viewing software may be used in these activities.

TRADITIONAL DATA PRODUCTS, EXISTING DATA AND THE PROVINCIAL DATA ARCHIVE

Printed and digital (pdf) format reports and maps will be produced from aquifer-mapping projects. The pdf format documents may be distributed on CD-ROM, and from on-line information systems such as Land Information Ontario (LIO).

The project data archive will also be a very important data product. Its data should transfer smoothly into LIO, where clients can use it together with other land and water information.

The existing data portion of Figure 32.2 represents all the existing data that may be useful for aquifer mapping. Examples of these data include published MNDM geology maps and the Ministry of the Environment water well records database.

DATA MODELS

There are 5 distinct data models required for aquifer mapping:

- vector geographic information system (GIS) data models;
- relational database model for point locations including boreholes;
- geological cross-sections and profiles;
- raster surfaces;
- 3-D solid modelling of the Earth.

Vector Geographic Information System Data Models

The "surface map" data, such as topography and geology, are handled as two-dimensional GIS data using desktop software. The data may be conceptualized as a set of map layers, where each layer has an attribute table describing objects within the layer. The details of this vector GIS data are similar to the Ontario Geological Survey seamless Quaternary geology map (Bajc et al. 2001).

Relational Database Model for Point Locations (Including Boreholes)

During an aquifer-mapping project data about point locations, including boreholes, will be stored in a desktop relational database management system, such as Microsoft Access. In addition, information regarding observation points, such as test pits and natural and man-made exposures, can be stored in this database. Borehole information is a key component of aquifer mapping.

A data model diagram for the point location database is shown in Figure 32.3. Because data will need to be exchanged with other agencies, an effort has been made to achieve compatibility with the following existing databases:

- Oak Ridges Moraine NATMAP – Hydrogeology Network Database used by the Geological Survey of Canada since the mid-1990s (Russell et al. 1996).
- York–Peel–Durham (YPD) database created in 2002 by Earth*fx* earth science information systems for use in the Oak Ridges Moraine – Conservation Authorities Coalition hydrogeology work in the Greater Toronto Area (L. Davidson, Earth*fx*, personal communication, 2002). Contractors doing municipal groundwater studies under Ministry of the Environment funding are also using this database.
- Ministry of the Environment water well records database, used to maintain information about water wells drilled across Ontario (T. Cheng, Ontario Ministry of the Environment, personal communication, 2001). This database is virtually identical to the borehole database, which was used by the Grand River Conservation Authority in their hydrogeology studies (J. Pitcher, Grand River Conservation Authority, personal communication, 2002).
- Region of Waterloo water resource analysis system, used by the Regional Municipality of Waterloo to maintain information about boreholes and related information (J. Robinson, Regional Municipality of Waterloo, personal communication, 2002).
- Ministry of the Environment's provincial groundwater monitoring information system, used to maintain information from the network of groundwater monitoring wells (Ontario Ministry of the Environment, personal communication with data analysts, 2002).
- Ontario petroleum data system (T. Carter, Ontario Ministry of Natural Resources, personal communication, 2002).

Geological Cross-Sections and Profiles

Cross-sections are drawings of the geology within the Earth along a vertical plane connecting 2 points on the surface. A collection of cross-sections may be used to represent three-dimensional geology in a series of "slices".

The term "profile" is used for geophysical results such as a seismic reflection profile. Here, within a vertical plane along the seismic line, seismic reflectors may be seen, and these may represent the top of specific formations or the water table. Careful interpretation of these profiles is required to correctly infer geology from them.

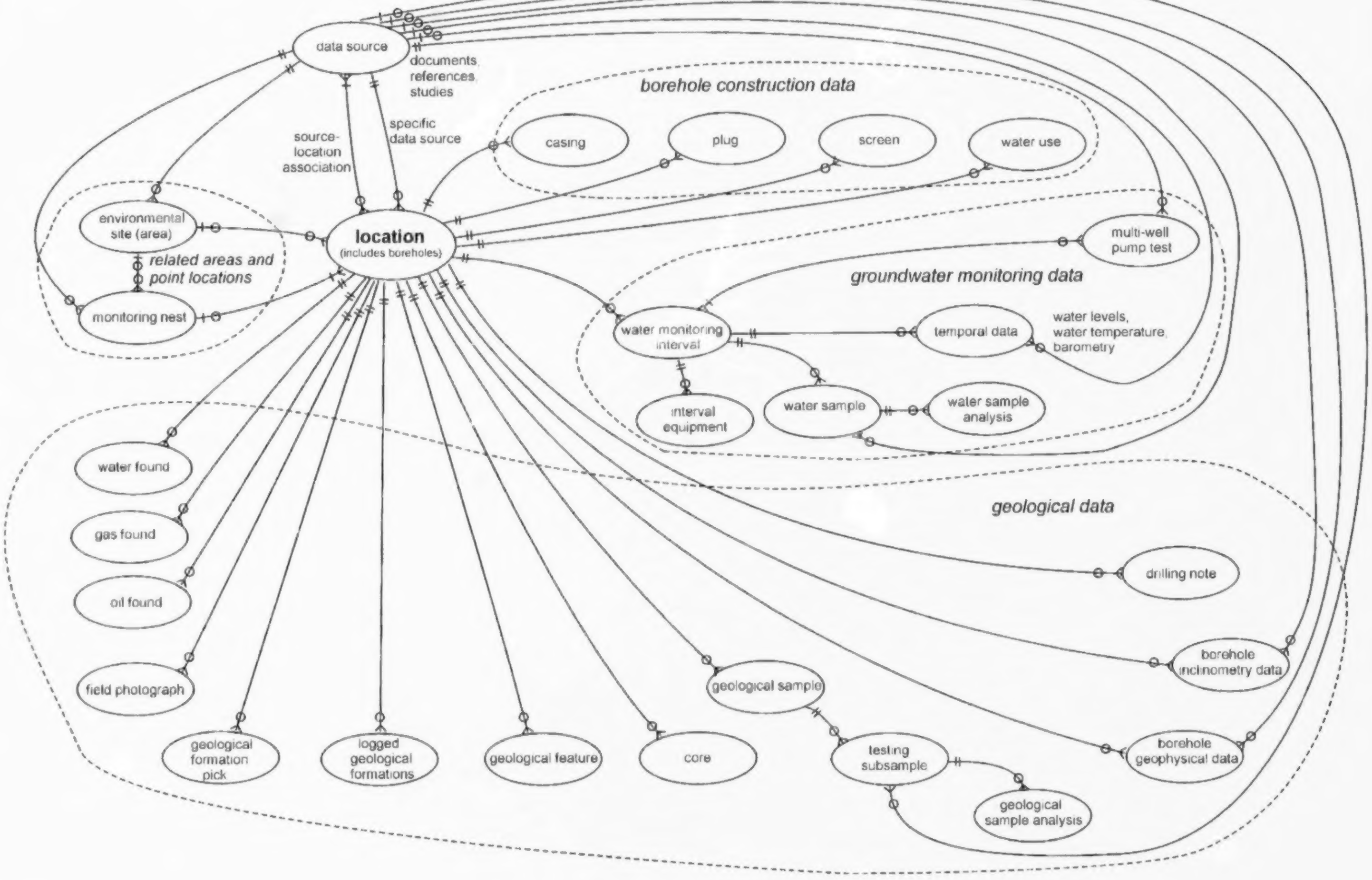

data source
documents, references, studies
source-location association
specific data source
location
(includes boreholes)
borehole construction data
casing
plug
screen
water use
environmental site (area)
related areas and point locations
monitoring nest
multi-well pump test
groundwater monitoring data
water monitoring interval
temporal data
water levels, water temperature, barometry
interval equipment
water sample
water sample analysis
geological data
water found
gas found
oil found
field photograph
geological formation pick
logged geological formations
geological feature
core
geological sample
testing subsample
geological sample analysis
drilling note
borehole inclinometry data
borehole geophysical data

Figure 32.3. Data model diagram for point locations, including boreholes.

Geological cross-sections provide source data for aquifer-mapping projects, but they also provide a vehicle for visualizing subsurface geology from projects. Most cross-sections and profiles used as source data in a project will be paper, printed materials from a map surround or figures in geological reports. For aquifer mapping, it is proposed to scan these materials, rubber-sheet them as necessary, and then "hang" these raster images vertically within the software environment for interpretation. With specialized software, it is possible to visually "pick" the tops and bottoms of geological formations from cross-sections and profiles, and store the results in the point location database.

Raster Surfaces

Raster data used in aquifer mapping comprise

- imagery such as digital orthophotos and images representing geophysical data and other "parametric data". These images are viewed in the software environment together with other data, such as geological contacts, borehole locations, etc.;
- elevation surfaces representing the land surface (digital elevation model), tops (and bottoms) of geological formations, the top of the water table, etc.;
- parametric surfaces representing, for example, the value of a geophysical parameter, soil geochemistry, thickness of a geological formation (isopach map) or surface drainage direction for each pixel in (0 to 360) degrees.

Raster data are represented as rectangular "cells" having a standard length and width, and which are georeferenced. The data are created and visualized using various software, but it is recommended that they should be stored in the project archive in ESRI Grid format.

Three-Dimensional Solid Modelling of the Earth

The three-dimensional cell model is an effective way to model and visualize three-dimensional geology and hydrogeology information. This method of data management is used in the GoCad software that is used at the Mining Innovation, Rehabilitation and Applied Research Corporation (MIRARCO) in Sudbury for mining and exploration purposes. The 3-D cell model is also used in hydrogeological software such as Modflow and Viewlog, to model groundwater flow. These latter software may use variable-sized cells within the model to allow a detailed representation of formations with relatively moderate data storage requirements.

SOFTWARE SUGGESTIONS

Table 32.1 lists possible software choices for aquifer mapping. For several of the tasks, data sets and data models in aquifer mapping, there are suitable standard software products being used within MNDM and the other Ontario Land and Resources Cluster (LRC) ministries (Ministry of the Environment, Ministry of Natural Resources, and Ministry of Agriculture, Food and Rural Affairs). These software include ESRI geographic information system software, and the Microsoft Access and Oracle database management systems. These software can provide the "project data archive" shown in the data flow diagram (*see* Figure 32.2).

Table 32.1. Possible software choices for aquifer mapping.

Type of Data	Land and Resources Cluster Standard Software	Specialized Software
Vector GIS data	ESRI desktop GIS software: ArcInfo 8.x, ArcView 8.x and ArcView 3.x	
Relational database data	Microsoft Access (97) for desktop, Oracle on servers	
Scanned cross-sections and profiles	Corel PhotoPaint for viewing, editing	ViewLog, Rockworks for obtaining stratigraphic "picks"
Surfaces	ArcInfo grid files may be viewed and stored using ESRI Spatial Analyst and 3D Analyst	For creating surfaces: Viewlog, Surfer, PCI Easi Pace
3-D cell data and perspective views		GoCAD: powerful cell modeller and 3-D environment; ESRI 3D Analyst perspective views; ViewLog, Rockworks: various capabilities.

For other tasks, such as "picking" formation tops from scanned images of cross-sections, interpolating point and contour data, and performing hydrogeological modelling, there is no LRC-standard software. However, there is software, although not formally standard, already being used within the LRC which can do some of these tasks. This software includes ViewLog, Surfer and PCI Easi-Pace. Rockworks software is used by the Ohio Geological Survey for some of these tasks, and GoCAD is used by the Mining Innovation, Rehabilitation and Applied Research Corporation (MIRARCO) for three-dimensional modelling of geology. MIRARCO has office space and a virtual reality data-viewing facilty in the building occupied by MNDM in Sudbury.

In MNDM's aquifer-mapping work, a survey and evaluation of available software will be undertaken, and suitable software packages will be selected for tasks where there is not suitable Cluster-standard software available.

IMPLEMENTATION AND NEXT STEPS

Now that MNDM has a recommended data organization for aquifer mapping, it needs to be implemented. In 2002 to 2003, MNDM may

- acquire necessary "specialized" software for the data visualization and analysis part of aquifer mapping. Tasks such as looking at available options, performing comparisons, and perhaps using competing products in parallel to find what works best will be undertaken.
- build physical databases and software working environments following the recommended data organization, and also build desktop applications as needed for data collection and processing. Simple Microsoft Access forms for field data were already built and used in the 2002 field season.
- import required data for study areas, and manually enter field data and data from existing consultant reports. Use the data systems to process and manage data in our aquifer mapping projects.
- work with LIO staff to ensure there will be a home for aquifer mapping data in the provincial data archive.

ACKNOWLEDGMENTS

Many people helped MNDM with this project by working group participation, discussions or providing data models or data. These people include: S. Hamilton, A. Bajc, D. Armstrong and P. Barnett at MNDM; L. Davidson and D. Kassenaar at Earth*fx*; D. Sharpe, H. Russell and C. Logan at the Geological Survey of Canada; P. Lapcevic, D. Boyd, J. Pitcher and S. Bellamy at the Grand River Conservation Authority; G. Kaltenecker, T. Cheng, R. Bruce and S. Emami at the Ministry of Environment, J. Robinson at the Regional Municipality of Waterloo; and T. Carter, J. Ernsting, W. Hayes, A. Trudell, S. Christilaw, B. Matthews and F. Kenny at the Ministry of Natural Resources.

John Dodge of MNDM participated in many of the meetings and took detailed notes.

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Corel PhotoPaint is a registered trademark of Corel Corporation.

ESRI, ArcInfo, ArcView, Grid, Spatial Analyst and 3D Analyst are registered trademarks of Environmental Systems Research Institute, Incorporated.

GoCAD is a trademark of T-Surf Corporation.

Microsoft and Microsoft Access are registered trademarks of Microsoft Corporation.

Modflow is the MODular three-dimensional finite-difference ground-water FLOW model, which was developed by the United States Geological Survey and incorporated in various commercial software products.

Oracle is a registered trademark of Oracle Corporation.

PCI Easi-Pace is a registered trademark of PCI Geomatics.

Rockworks is a trademark of RockWare Incorporated.

Surfer is a registered trademark of Golden Software Incorporated.

Viewlog software is a product of Viewlog Systems, Toronto.

33. Project Unit 00-032. Evaluation of Selected Southern Ontario Shales

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INTRODUCTION

In 2000, the Ontario Geological Survey (OGS) initiated a study of the Upper Ordovician Queenston Formation, the main source of shale for the province's brick industry. This study was undertaken because, in the area where this unit is presently being extracted, the Toronto–Brampton–Hamilton area, increasing land-use pressures may restrict future access to this important resource.

In 2000, the Queenston Formation shales were examined in operating quarries, major outcrops, and existing and new drill cores (Armstrong 2000). Areas of thin drift over the Queenston Formation were specifically targeted for evaluation, both within the area of present extractive activity and along the main outcrop belt of this formation. Samples, obtained from quarry and natural outcrop exposures, and drill cores, were analyzed geochemically, and selected core intervals were subjected to ceramic testing. Data from these analyses were presented in Miscellaneous Release—Data (MRD) 77 (Armstrong 2001a) and MRD 92 (Armstrong and Frederic 2001), and results of the first year of the study were presented in OGS Open File Report 6058 (Armstrong 2001b).

In 2001, the scope of this project was expanded to include a comparative study of 2 other Upper Ordovician shale units, the Blue Mountain and Georgian Bay formations (Armstrong 2001c). Field work was conducted in the summer of 2001 and a drilling program undertaken in the fall and winter. This phase of the project also addressed areas underlain by the Queenston Formation that were not covered by the 2000 field program (e.g., eastern Ontario). Geochemical analyses of samples obtained during the field component of the 2001 program are presented in MRD 107 (Armstrong and Sergerie 2002a). Data from the 2001–2002 drilling program are presented in MRD 112 (Armstrong and Sergerie 2002b) and results of the 2001 field work and drilling program are presented an Open File Report (Armstrong and Sergerie 2002c).

GEOLOGICAL OVERVIEW

The Upper Ordovician Queenston, Georgian Bay and Blue Mountain formations crop out in a belt east of and parallel to the Niagara Escarpment (Figure 33.1). Their equivalent units in eastern Ontario (Table 33.1), the Queenston, Carlsbad and Billings formations, occur in fault-bounded blocks that extend eastward from Ottawa to the Quebec border (Figure 33.2).

The Queenston, Georgian Bay and Blue Mountain formations (and their equivalent units in eastern Ontario) are part of a thick clastic wedge that was deposited as a result of the Taconic Orogeny during the Late Ordovician. The oldest of these units, the Blue Mountain Formation, consists mainly of grey shales, with subordinate amounts of thin-bedded limestone and calcareous sandstones and siltstones. This unit is gradationally overlain by the interbedded grey-green shales, limestones and calcareous sandstones and siltstones of the Georgian Bay Formation. The youngest of these units, the Queenston Formation, consists

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of mainly of red, silty, calcareous shales with subordinate green silty calcareous shales, and light red and grey-green, fine-grained, calcareous sandstones and siltstones and minor limestones. These 3 units represent a conformable shallowing-upward succession, from deep shelf (Blue Mountain Formation), through to storm-influenced shallow shelf (Georgian Bay Formation) to tidal flat and possibly terrestrial conditions (Queenston Formation). Details regarding the geology of these units is reviewed by Armstrong and Sergerie (2002c) and Hamblin (1998, 1999). Their resource potential and ceramic properties have been reviewed by Kwong, Martini and Narain (1985), Martini and Kwong (1986), Guillet (1967, 1977) and Guillet and Joyce (1987).

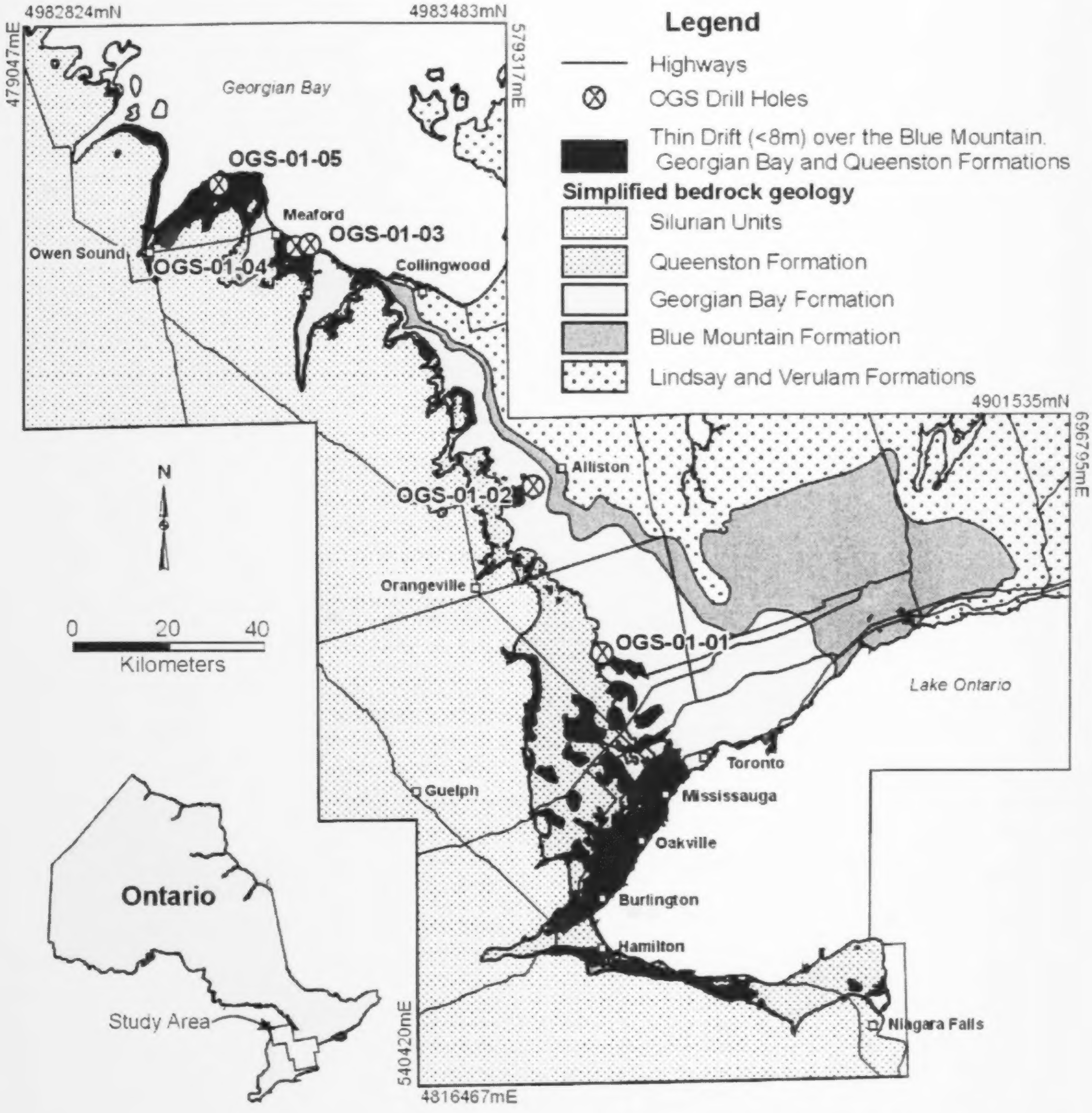
4982824mN
4983483mN
479047mE
579317mE
Georgian Bay
Legend
Highways
OGS Drill Holes
Thin Drift (<8m) over the Blue Mountain. Georgian Bay and Queenston Formations
Simplified bedrock geology
Silurian Units
Queenston Formation
Georgian Bay Formation
Blue Mountain Formation
Lindsay and Verulam Formations
OGS-01-05
Meaford
OGS-01-03
Owen Sound
OGS-01-04
Collingwood
4901535mN
696795mE
Alliston
OGS-01-02
N
0
20
40
Kilometers
Orangeville
OGS-01-01
Lake Ontario
Toronto
Mississauga
Guelph
Oakville
Ontario
Burlington
Hamilton
Study Area
Niagara Falls
540420mE
4816467mE

Figure 33.1. Generalized bedrock geology map of south-central Ontario, showing the distribution of the Queenston, Georgian Bay and Blue Mountain formations, areas of thin drift over these units, and locations of the 2001 OGS drill holes (*after* Armstrong and Sergerie 2002c).

Table 33.1. Upper Ordovician and Lower Silurian stratigraphic chart for the Niagara Escarpment area, southern Ontario and for eastern Ontario (*from* Johnson et al. 1992). Note: "Fm" = Formation; "Mb" = Member.

Age	Geographic Areas			
	Niagara Peninsula area	**Alliston – Collingwood area**	**Owen Sound – Meaford area**	**Eastern Ontario**
Lower Silurian	Whirlpool Fm	Manitoulin Fm	Manitoulin Fm	*not preserved*
		Whirlpool Fm		
Upper Ordovician	Queenston Fm	Queenston Fm	Queenston Fm	Queenston Fm
	Georgian Bay Fm	Georgian Bay Fm	Georgian Bay Fm	Carlsbad Fm
	Blue Mountain Fm	Blue Mountain Fm	Blue Mountain Fm	Billings Fm
	Collingwood Mb (Lindsay Fm)	Collingwood Mb (Lindsay Fm)	Collingwood Mb (Lindsay Fm)	Eastview Mb (Lindsay Fm)

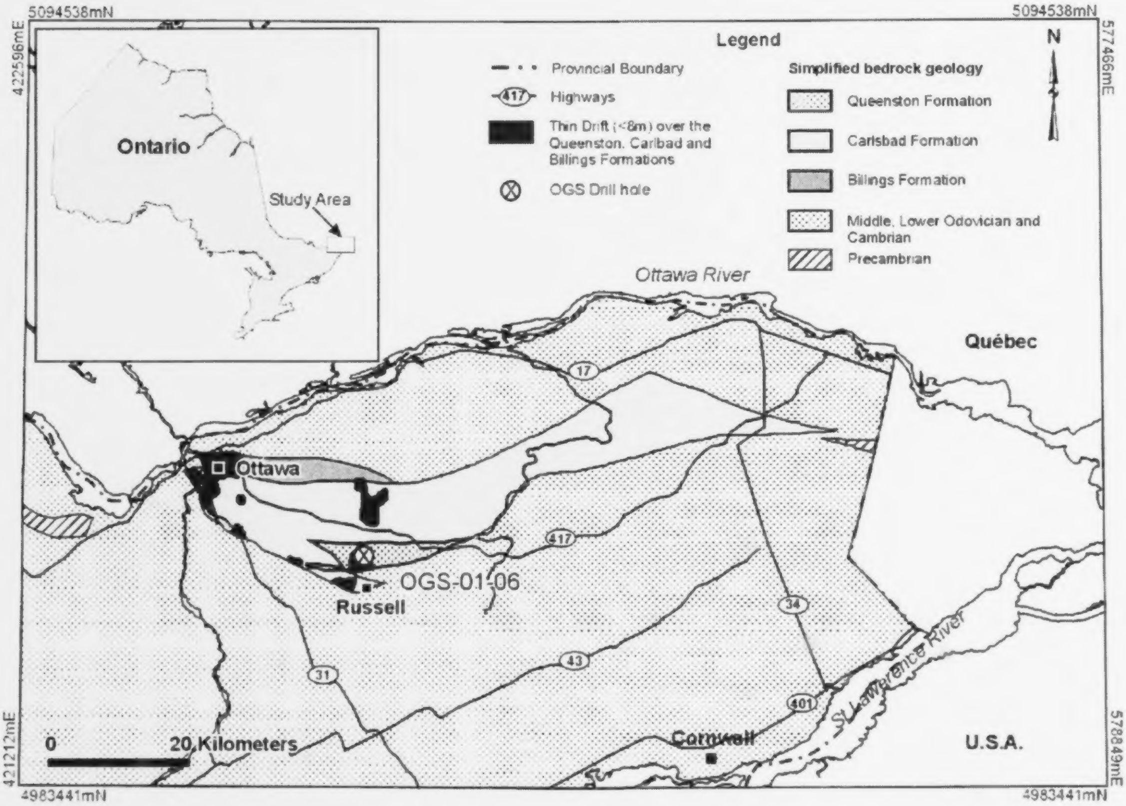
5094538mN
5094538mN
422596mE
577466mE
Legend
Provincial Boundary
Highways
Thin Drift (<8m) over the Queenston, Carlbad and Billings Formations
OGS Drill hole
Simplified bedrock geology
Queenston Formation
Carlsbad Formation
Billings Formation
Middle, Lower Odovician and Cambrian
Precambrian
N
Ontario
Study Area
Ottawa River
Québec
17
Ottawa
417
OGS-01-06
Russell
34
43
31
401
St. Lawrence River
0
20 Kilometers
Cornwall
U.S.A.
421212mE
578849mE
4983441mN
4983441mN

Figure 33.2. Generalized bedrock geology map of eastern Ontario, showing the distribution of the Queenston, Carlsbad and Billings formations, areas of thin drift over these units, and the location of OGS drill hole OGS-01-06 (*after* Armstrong and Sergerie 2002c).

The initial factor governing the economic potential of any bedrock resource is the thickness of drift cover. Published drift thickness maps cover most of the outcrop belt of the Queenston, Georgian Bay and Blue Mountain formations and their equivalents in eastern Ontario (e.g., Golders Associates Ltd. and Rowell 1996; Rowell 1997). Areas underlain by these formations with less than 8 m drift cover are highlighted in Figures 33.1 and 33.2.

RESULTS OF 2000 FIELD AND DRILLING INVESTIGATIONS

Key results obtained from the initial phase of the study (Armstrong 2001b), included

- the carbonate content in the Queenston Formation (a prime factor in determining brick colour) appears to be largely controlled by calcite content, and is effectively approximated by CO_2 content;
- shale with a CO_2 content up to 10% yields red coloured bricks, whereas shale with a CO_2 content ranging from 10 to 15% yields yellow-buff coloured bricks (shale with a higher average CO_2 content was not encountered in the presently active quarries);
- the middle part of the Queenston Formation is the most calcareous (the Burlington Quarry is located in this part of the formation and produces yellow-buff coloured bricks);
- confirmation that the Queenston Formation as a whole becomes more calcareous towards the north, and that the middle part of the formation remains the most calcareous part in the north (includes significant fossiliferous limestone beds);
- in the northern part of its outcrop belt, northwest of Collingwood, intervals of the Queenston Formation, especially toward the top and bottom of the formation, have carbonate contents comparable with the middle part of the formation in the south (i.e., 10 to 15% CO_2);
- elevated sulphur content in the Queenston Formation indicates the presence of gypsum (a deleterious component in brick making), but there appears to be little sulphur in the matrix in the vicinity of gypsum nodules or fracture-filling gypsum (i.e., the nodule or fracture must be sampled to indicate its presence);
- in a core through the whole formation at Milton (OGS-83-1), gypsum nodules and fracture fillings occur from approximately 50 m below the top of the Queenston Formation and throughout the remainder of the formation (a further 110 m down this hole), although they are most abundant in a zone from 50 to 60 m below the top.

Iron content (reported as Fe_2O_3) is also a primary contributor to the red colouration of bricks, and so the ratio of Fe_2O_3 to CO_2, combining both iron and carbonate factors, is a good indicator of potential brick colour. Fe_2O_3/CO_2 ratios calculated from the 2000 active quarry data (*from* Armstrong 2001a, 2001b), indicate that values below 0.50 yield yellow-buff coloured bricks.

RESULTS OF 2001 FIELD AND DRILLING INVESTIGATIONS

In 2001, additional sources of Queenston Formation data were investigated (Armstrong 2001c) and the study expanded to include examination of the Georgian Bay and Blue Mountain formations. Well-documented outcrops along the rivers and creeks in the Toronto and the Meaford areas, and those forming large bluffs along the shore of Georgian Bay between Thornbury and Owen Sound were measured and sampled for geochemical analysis. The resulting data are presented in Armstrong and Sergerie (2002a, 2002c). In addition, 5 drill holes were cored in the fall of 2001 to obtained fresh, stratigraphically controlled samples of these 2 formations. Data from this drill program are presented in Armstrong and Sergerie (2002b, 2002c). The locations and basic stratigraphic information for these holes are presented in Table 33.2.

Table 33.2. Preliminary results of 2001 Ontario Geological Survey drilling program (note: UTM coordinates in NAD 83; all units reported in metres). Detailed logs of these holes are presented in Armstrong and Sergerie (2002b, 2002c).

Hole #	General Location	UTM Easting	UTM Northing	Overburden Thickness	Total Depth Drilled	Bedrock Units (thickness)
OGS-01-01	Tullamore, northeast of Brampton	598950	4850250	1.50	32.00	Georgian Bay (30.50 m)
OGS-01-02	east of Rosemont, west of Alliston	584657	4885765	2.25	37.72	Georgian Bay (35.47 m)
OGS-01-03	Christie Beach Road, east of Meaford	538606	4937283	1.60	44.12	Blue Mountain (42.52 m)
OGS-01-04	southeast of Meaford	536270	4936455	0.00	61.08	Queenston (13.82 m), Georgian Bay (47.26 m)
OGS-01-05	Balaclava, northwest of Meaford	519274	4948872	2.59	61.27	Queenston (2.09 m), Georgian Bay (56.59 m)
OGS-01-06	Russell Quarry, east of Ottawa	470909	5016616	1.50	60.96	Queenston (21.45 m), Carlsbad (38.01 m)

Table 33.3. Average content of selected elements for lithologically grouped bed samples from the Queenston, Georgian Bay and Blue Mountain formations. Samples were collected from outcrops in 2001. Full data sets are presented in Armstrong and Sergerie (2002a, 2002c). Mixed shale–non-shale samples are included in the "all" sample data sets, but not shown here as separate sample groups. Note: element oxide contents reported as weight percent; "n" = number of samples in data set.

Sample Group Data Set	n	SiO_2	Al_2O_3	MgO	CaO	Fe_2O_3	LOI	CO_2	S	Fe_2O_3/ CO_2
all Queenston bed samples	62	44.96	12.77	3.71	12.90	5.43	15.14	10.89	0.01	0.72
all Georgian Bay bed samples	56	57.14	15.04	3.27	4.53	6.29	7.79	4.47	0.29	2.34
all Blue Mountain bed samples	31	55.00	15.83	3.36	4.33	6.64	8.30	6.10	0.75	1.71
Queenston shale samples	49	46.06	13.85	3.72	11.11	6.06	13.88	9.47	0.01	0.85
Georgian Bay shale samples	42	57.89	16.71	3.43	2.44	6.76	6.43	2.72	0.30	2.87
Blue Mountain shale samples	25	56.66	16.92	3.25	2.54	6.78	7.00	4.45	0.76	1.92
Queenston non-shale samples	13	40.78	8.73	3.69	19.67	3.05	19.89	16.25	0.02	0.23
Georgian Bay non-shale samples	11	54.99	8.64	2.72	12.06	4.52	12.71	10.89	0.25	0.57
Blue Mountain non-shale samples	6	48.07	11.30	3.82	11.76	6.04	13.69	12.97	0.71	0.86

In both phases of this study (i.e., in 2000 and 2001), 2 types of samples were taken: composite or continuous channel samples perpendicular to bedding; and individual bed or spot samples. Composite samples are useful for determining bulk geochemical properties of a lithologic unit at a specific location, whereas bed samples are useful in determining the lithologic constituents of a unit. A summary of the bed sample data for the 2001 field outcrop samples is presented in Table 33.3.

Table 33.3 indicates that the Queenston Formation, including both its shale and non-shale components, is the most calcareous of the 3 formations (higher CO_2 and CaO). Although the non-shale components of the Georgian Bay and Blue Mountain formations are calcareous, the shale samples of these units are not. Both the Georgian Bay and Blue Mountain formations have a higher sulphur content than the Queenston Formation. Sulphur occurs mainly as sulphides (pyrite) in the Georgian Bay and Blue Mountain formations.

Non-shale components in all of these units, commonly called hard beds or hard bands, consist of fine- to coarse-grained bioclastic limestone (or calcarenite), fine-grained calcareous sandstones and siltstones, and calcisiltites (i.e., limestones composed of silt-sized particles). All of these types of hard beds are common in the Georgian Bay Formation. They also all occur in the Blue Mountain Formation, where they tend to be thinner and much less abundant. All but the bioclastic limestone component are also common in the Queenston Formation, however, the uppermost part of the formation (approximately 20 m) contains very few if any hard beds, and bioclastic limestone occurs in the middle of this formation northwest of Collingwood.

Coarse-grained bioclastic limestones are undesirable for brick making, because the large calcite crystals "pop-out" during firing. So locally, the Georgian Bay Formation, and the middle part of the Queenston Formation in the north, may not be suitable for brick making. The other hard beds in these units are actually beneficial for making bricks, as they are sources of important non-clay constituents. They can, however, cause problems in extraction if they are too thick (e.g., >15 cm) or too abundant.

In eastern Ontario, the Queenston Formation is less calcareous, more siliceous and harder. The Russell Quarry exposes approximately 13 m of the Queenston Formation with an average of 2.97% CO_2, 59.53% SiO_2 and an Fe_2O_3/CO_2 ratio of 2.44 (Armstrong and Sergerie 2002c). In the winter of 2002, a hole, OGS-01-06, was drilled from the top of the east wall of the Russell Quarry to a depth of 60.97 m. The basal contact of the Queenston Formation with the underlying grey shales and limestones of the Carlsbad Formation was encountered at a depth of 22.95 m, or approximately 10 m below the floor of the quarry.

CERAMIC TESTING

Intervals of some of the 2000 drill cores were submitted to the National Brick Research Center, in Anderson, South Carolina for ceramic properties testing. Test methodology and complete results are presented in Armstrong and Frederic (2001) and Armstrong and Sergerie (2002c). Results of this testing are presented in Table 33.4.

Analysis of these results and the plots of thermal expansion and simultaneous differential thermal analysis and thermal gravimetric analysis for these samples (*see* Armstrong and Frederic 2001; Armstrong and Sergerie 2002c) provide insight into the brick-making potential of the Queenston Formation at various stratigraphic levels and geographic areas: sample A1A is from the middle of the Queenston Formation near Burlington; sample A6A is from the upper-middle part of the formation southeast of Milton; sample B1A is from the upper part of the formation west of Mansfield; and sample C2A is from the uppermost part of the formation northwest of Meaford.

Samples B1A and C2A yielded the best overall results (J.C. Frederic, National Brick Research Center, personal communication, 2002). They have the highest amount of clay, lowest SiO_2, highest Fe_2O_3, highest strength values (*see* Table 33.4) and relatively normal thermal expansion plots (Armstrong and Frederic 2001; Armstrong and Sergerie 2002c).

Table 33.4. Summary of ceramic test results and geochemical analyses for core samples of the Queenston Formation. The complete data set is published in Armstrong and Frederic (2001) and Armstrong and Sergerie (2002c). Note: strength = modulus of rupture; psi = pounds per square inch.

	Drill holes:	**OGS-00-A1**	**OGS-00-A6**	**OGS-00-B1**	**OGS-00-C2**
	Sample #:	**A1A**	**A6A**	**B1A**	**C2A**
	Depth range of sample below surface in drill hole:	4.65 – 14.97 m	6.55 – 16.53 m	8.46 – 18.30 m	0 – 13.24 m
Firing and Properties Tests	dry shrinkage (%)	0.73	1.67	2.90	3.12
	fired shrinkage (%)	0.35	0.46	1.03	0.92
	total shrinkage (%)	1.12	2.15	3.89	4.13
	cold absorption (%)	17.57	19.75	13.91	15.38
	boiled absorption (%)	20.58	21.28	16.85	18.08
	cold/boiled absorptions	0.85	0.93	0.83	0.85
	density (g/cc)	1.76	1.75	1.80	1.72
	porosity (%)	36.16	37.28	30.37	31.05
	green strength (psi)	125.3	124.0	141.9	164.4
	dried strength (psi)	186.8	142.7	188.7	219.6
	fired strength (psi)	786.8	733.0	1257.4	1283.9
	efflorescence	yes	yes	yes	yes
	fired colour	tan with white discolouration	light pinkish tan with white discolouration	medium pinkish tan	light pinkish tan
Geochemistry	LOI (%)	15.99	15.36	15.54	15.61
	CO_2 (%)	12.43	11.13	11.11	11.86
	CaO (%)	15.09	12.99	12.86	12.38
	SiO_2 (%)	44.24	45.63	43.99	41.83
	Al_2O_3 (%)	11.33	12.31	13.16	14.01
	Fe_2O_3 (%)	4.91	4.95	5.51	6.13
	Fe_2O_3/CO_2	0.39	0.44	0.50	0.52

CONCLUSIONS

The Queenston Formation is the preferred source of shale for the brick industry for a variety of reasons, not the least of which is the proximity of large areas of high-quality shale resources close to surface and close to markets. Increased urbanization in the traditional areas of shale extraction have restricted access to this resource and will likely continue to do so in the future. A few relatively undeveloped areas with thin drift over the Queenston Formation remain in the area west of Toronto and should be considered for protection as future shale resources.

Other small areas of thin drift over the Queenston Formation, outside of the Niagara Escarpment Plan Area (NEPA), notably, areas near Niagara-on-the-Lake, west of Mansfield, west of Duntroon, and southeast of Meaford, should also be considered for resource protection. Many of these areas overlie the uppermost part of the formation, which has the best qualities for brick making.

The largest undeveloped area of thin drift over the Queenston Formation (outside of the NEPA) is located between Meaford and Owen Sound. Drilling and testing indicates a relatively high quality shale resource in the upper part of this formation. Although located a long way from present markets, this may represent the largest long-term source of brick shale in the province and should be considered for protection from resource sterilization.

The Queenston Formation shale in eastern Ontario is of high quality and is presently being quarried for brick making by Canada Brick Ltd. The remaining small area of thin drift over this unit in this area should be protected for shale resource extraction.

The Georgian Bay Formation has a long history of extraction for use by the brick industry in Toronto and Mississauga, however, these areas have long since been urbanized and future extraction in the Toronto area seems highly unlikely. North of Toronto, this unit is largely covered by thick Quaternary deposits. Areas of thin drift over the Georgian Bay Formation do exist in the Rosemont area west of Alliston and this area may prove to be a good source of shale for brick making.

The Georgian Bay Formation is exposed or covered by thin drift in the area southeast of Meaford. In this area, this unit may be good source of shale for the brick industry as long as coarse-grained bioclastic limestone beds and/or zones of abundant hard beds are avoided. This unit may be extracted with the lower part of the overlying Queenston Formation (e.g., in the vicinity of drill hole OGS-01-04) or the upper part of the Blue Mountain Formation (e.g., between drill hole OGS-01-03 and East Meaford Creek).

Little is known about the brick-making potential of the Carlsbad Formation, the equivalent of the Georgian Bay Formation in eastern Ontario. Only a few small areas of thin drift over the Carlsbad Formation are known.

The Blue Mountain Formation is generally poorly exposed, with the best exposures in deep valley east of Toronto and in bluffs southeast of Meaford. Except for a relatively high sulphur content (as sulphides), this unit may prove to be a good source of brick-making shale where it is accessible. The best site for extraction appears to be southeast of Meaford where it is overlain by thin drift and/or the lower part of the overlying Georgian Bay Formation.

Thin drift areas over the Billings Formation, the equivalent unit to the Blue Mountain Formation in eastern Ontario, are mainly covered by the city of Ottawa.

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Geoscience Laboratories

34. Improvements in the Accuracy and Sensitivity of Water Analyses by the Application of Inductively Coupled Plasma Dynamic Reaction Cell™ Mass Spectrometry

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INTRODUCTION

The concentrations of trace elements in lake and river waters depend on the interaction of many different factors. For many trace elements, the most important of these is the weathering of bedrock or suspended sediments (Simpson et al. 1993; McConnell et al. 1993), but anthropogenic inputs (either via the atmosphere or directly in the form of industrial effluents or mine drainage), adsorption onto particulate matter, algal scavenging, and direct precipitation of authigenic minerals may also affect element concentrations. Because so many different processes can affect the compositions of fresh waters, the accurate analysis of trace elements at low concentrations has a wide range of economic and environmental applications, including geochemical mapping (Fortescue and Dyer 1994), mineral exploration (Jackson 1995; Dyer 1998; Jackson 2002), and the study of metal contamination associated with mining activities or waste disposal (e.g., Pearson et al. 1999; Bredehoeft 1984).

When compared to the analysis of the associated sediments, water analyses offer many advantages, including

1. limited sample preparation (waters require only filtration and acidification whereas sediments must be dried, disaggregated and either dissolved or leached prior to analysis),
2. the ability to perform direct analyses, without prior digestions, leading to faster data acquisition,
3. relatively simple matrices that are comparable from sample to sample (and do not depend on grain size),
4. independence from scavenging and/or false enrichment by the formation of iron-manganese hydroxides (provided the correct layers are sampled).

However, the acquisition of a full suite of trace elements in fresh waters has many associated analytical difficulties, including element concentrations that are commonly close to the lower limits of detection for many instruments, the presence of a variety of interferences in spectra obtained by either inductively coupled plasma atomic emission spectrometry (ICP–AES) or inductively coupled plasma mass spectrometry (ICP–MS)(which limit the accuracy or precision of measurement), and potential contamination from laboratory equipment and/or reagents. Although steps can be taken to minimize the effects of contamination, the low concentrations of many elements and the spectral interferences during analysis have traditionally hampered accurate trace element analyses.

Summary of Field Work and Other Activities 2002, Ontario Geological Survey, Open File Report 6100, p.34-1 to 34-9.

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INDUCTIVELY COUPLED PLASMA MASS SPECTROMETRIC ANALYSIS OF FRESH WATERS

Most natural fresh waters contain trace elements concentrations that range from approximately 10 to 100 ppb (μg/L; e.g., Fe, Al, Ba, and Sr), to less than 1 ppt (ng/L; e.g., the rare-earth elements (REE), and/or high field strength elements (HFSE): Ti, Zr, Nb, Hf, Ta, Th, and U) and possess a matrix that commonly contains more than 10 ppm major ions (Na^+, Mg^{2+}, K^+, Ca^{2+}, CO_3^{2-}, Cl^-, and/or SO_4^{2-}). Although ICP–MS is able to analyze most of the elements that may be requested as part of a regional geochemical survey, the concentrations of many of the ultra-trace elements are often below the detection limits of older instrumentation and the method is affected by polyatomic interferences (formed by reactions between the matrix elements and/or plasma gases) on many of the more important trace elements (e.g., Ti, V, Cr, Fe, As, and Se). In order to analyze successfully the full suite of elements in natural fresh waters, a range of different methods may be employed to overcome these difficulties, including 1) pre-concentration of elements before analysis (using ion-exchange or solvent extraction techniques), 2) off- or on-line matrix separation (e.g., electrothermal vaporization or ultrasonic nebulization), 3) modification of plasma conditions so as to inhibit interferences (e.g., changing plasma gases or reducing the sample carrier gas flow or plasma temperature), 4) off-line correction of measured intensities, and 5) high-resolution ICP–MS. Whereas each of these techniques may be successful for the analysis of a limited group of elements, the benefits come at the cost of sample throughput, applicability to a large range of elements, cost of instrumentation or detection power. However, the recent coupling of a method of eliminating spectral interferences using low-pressure chemical reactions within the instrument (commercialized by Perkin–Elmer SCIEX, Concord, Ontario as the Dynamic Reaction Cell™ (DRC)) with a more sensitive spectrometer appears to have overcome many of the problems associated with low concentrations and interferences, leading to lower detection limits for all elements, including those that have previously been difficult by ICP–MS.

Until February 2001, waters were routinely analyzed at the Geoscience Laboratories (Geo Labs) using either a SPECTRO ICP–AES (major and selected trace elements; Geo Labs method Code IAW100) or a Perkin–Elmer ELAN 5000 ICP–MS (trace and ultra-trace elements; Geo Labs method code IMW100). Because neither of these instruments was sufficiently sensitive to analyze all the elements of interest, sample solutions were commonly introduced to the instruments by ultrasonic nebulization (during which the nebulized sample is heated so as to evaporate off most of the solvent, thereby increasing the amount of sample that reaches the plasma while reducing the amount of solvent present) in order to increase their sensitivity and/or reduce potential interferences. When applied to the ICP–AES instrument, such methods greatly improve the detection limits, but many trace and ultra-trace elements remain below detection in most fresh waters. When coupled with the ICP–MS instrument, these methods enable the determination of most trace element concentrations at sufficiently low concentrations, but were found to be insufficiently reliable for routine analyses.

In December 2000, Geo Labs took possession of an ELAN 6100DRC ICP–MS that is equipped with a dynamic reaction cell (DRC) for interference removal. Work with this instrument has shown that it is possible to not only eliminate many of the major interferences encountered during the analysis of fresh waters (when analyzing in dynamic reaction cell (DRC) mode), but also to improve the accuracy and precision of most trace element analyses when analyzing in standard mode. This report summarizes progress on the analysis of waters at Geo Labs and outlines possible future improvements.

POLYATOMIC INTERFERENCES IN INDUCTIVELY COUPLED PLASMA MASS SPECTROMETRY

The direct determination of elements of light to medium mass by ICP–MS is commonly hampered by the presence of "polyatomic" ions produced by reactions between the plasma gas and either the sample matrix or other analyte ions. Because the most intense interferences during argon ICP–MS are binary combinations between argon and light elements, including hydrogen, carbon, nitrogen, oxygen, and chlorine, the majority of the plasma-based interferences occur at masses between 40 and 80 amu and include spectral overlaps on the main isotopes of **Ca** ($^{40}Ar^+$ on $^{40}Ca^+$; $^{40}ArH_2{}^+$ on $^{42}Ca^+$), **V** ($^{35}Cl^{16}O^+$ on $^{51}V^+$), **Cr** ($^{40}Ar^{12}C^+$ or $^{35}Cl^{16}OH^+$ on $^{52}Cr^+$; $^{37}Cl^{16}O^+$ on $^{53}Cr^+$), **Mn** ($^{38}Ar^{16}OH^+$ or $^{37}Cl^{18}O$ on ^{55}Mn), **Fe** ($^{40}Ar^{14}N^+$ on $^{54}Fe^+$; $^{40}Ar^{16}O^+$, and $^{40}Ar^{17}O^+$ or $^{40}Ar^{16}OH^+$on $^{56}Fe^+$ and $^{57}Fe^+$), **As** ($^{40}Ar^{35}Cl^+$ on $^{75}As^+$), and **Se** ($^{40}Ar^{37}Cl^+$ on $^{77}Se^+$; $^{38}Ar^{40}Ar^+$ and $^{40}Ar^{40}Ar^+$ on $^{78}Se^+$ and $^{80}Se^+$). Depending on the sample matrix, other polyatomic interferences may also be present, including SO^+ and $SO_2{}^+$ ($^{32}S^{16}O^+$, $^{33}S^{16}O_2{}^+$, and $^{34}S^{16}O_2{}^+$, which isobarically overlap $^{48}Ti^+$, ^{65}Cu, and ^{66}Zn, respectively), element-oxygen dimers (e.g., $^{135}Ba^{16}O$ and $^{137}Ba^{16}O$, which overlap ^{151}Eu and ^{153}Eu, and oxides of many of the LREE, which overlap the HREE), or element-argon dimers (e.g., $^{63}Cu^{40}Ar$ and $^{65}Cu^{40}Ar$, which overlap ^{103}Rh and ^{105}Pd). Whereas the plasma-based polyatomic interferences affect all analyses, and are particularly important during the analysis of waters (where analyte concentrations are low), the intensities of the matrix- or sample-based interferences should vary between samples and only be important when there is a significant contrast in concentrations of the analyte and interfering ions. As a result, initial work with the DRC focussed on the efficient removal of the plasma-based interferences.

THE DYNAMIC REACTION CELL™

The DRC consists of a quadrupole mass analyzer located within an enclosed space within the ion optics chamber of the ICP–MS. It is pressurized with a reactive gas through which the ion beam from the plasma passes (Neubauer and Vollkopf 1999). The reaction gas is chosen so that it reacts with the interfering ions and either deionizes them or converts them to new polyatomic ions of a different mass. Because the DRC contains a quadrupole mass filter, the reaction products can be ejected from the ion beam while the analyte ions are able to pass through to the main mass analyzer where they are measured at their "normal" masses without the interfering ions. For the removal of argon-based interferences, the most commonly chosen reaction gas is ammonia owing to its rapid rate of reaction with Ar^+ ions, but slow rates of reaction with most analytes. However, other reaction gases (e.g., CH_4, H_2, and O_2) have also been used for more specialized applications. Because the reaction cell can be vented, and the reaction gas rapidly evacuated from the instrument, it is also able to operate as a conventional ICP–MS (standard mode analysis). The rapid conversion between modes enables the near-simultaneous analysis of samples using both DRC mode (for elements affected by interferences) and standard mode (for elements that are either unaffected by interferences or react with the reaction gas used).

RESULTS

Vanadium, Chromium, Manganese, and Iron

Figure 34.1 shows the variation in signals at masses 51 to 56 amu as a function of reaction gas flow rate for blank nitric acid solutions containing either methanol (as a source of carbon) or hydrochloric acid (as a source of chlorine) relative to similar solutions spiked with 50 to 200 ppt V, Cr, Mn and/or Fe. The initially steep gradients of the lines for the blank solutions indicate that the plasma-based interferences (^{35}ClO, ArC, ^{37}ClO, ^{38}ArO, ArOH, and ^{40}ArO) are rapidly removed by the reaction cell to leave only the analytes of interest (which react more slowly with the ammonia). The high count rates for chromium, manganese, and iron in the blank solutions at high gas flows indicate that either the blank acid or deionized water contained small amounts of the analyte elements, equivalent to approximately 10 ppt Cr, 3 ppt Mn and 20 ppt Fe. Although the signal for ^{56}Fe is significantly stronger than that for ^{54}Fe, the latter isotope was chosen for the determination of iron in fresh waters owing to the high calcium contents commonly found in such samples and the interference of ^{56}Fe by ^{40}CaO (which cannot be removed by reaction with ammonia in the DRC).

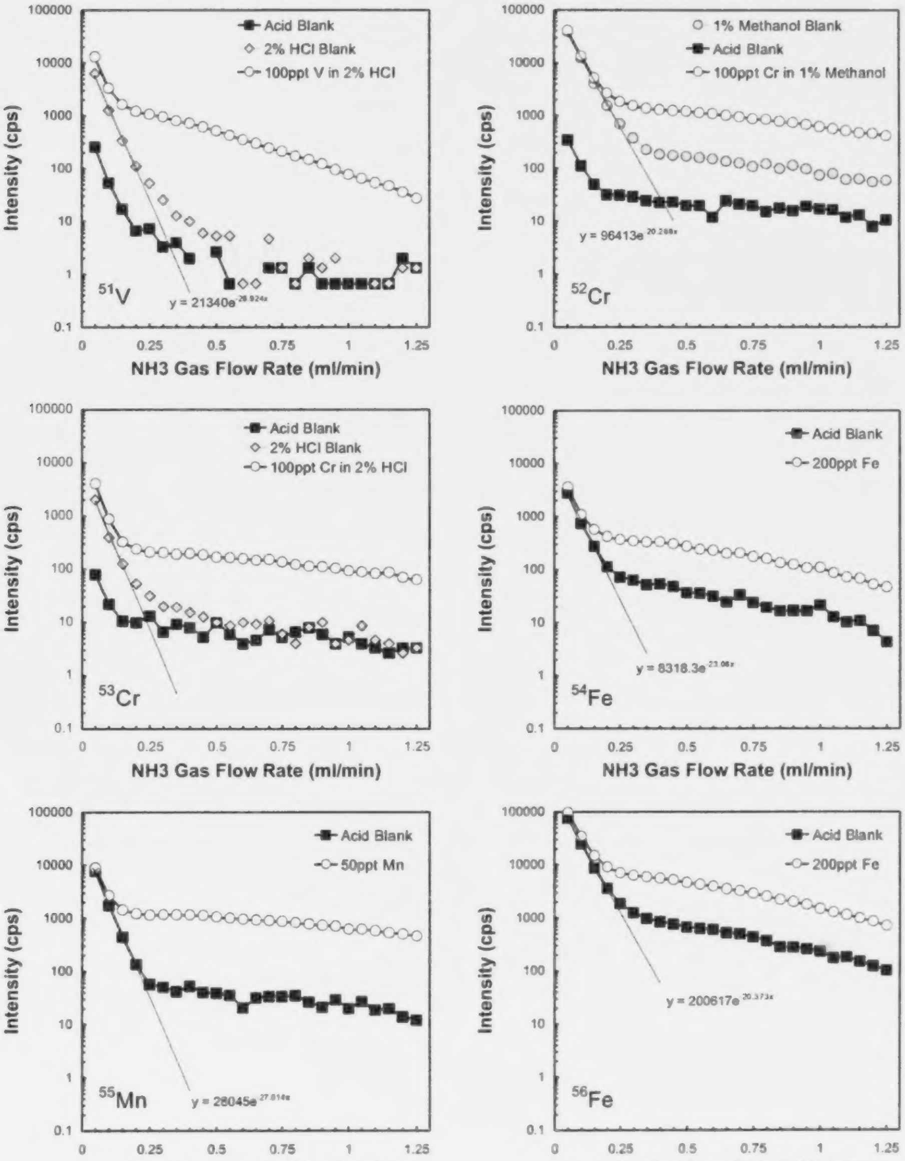

Figure 34.1. Plot of signal intensities at 51 to 55 amu as a function of gas flow for spiked and blank solutions of vanadium, chromium, manganese, and iron in 5% HNO_3 and either 1% methanol or 2% v/v HCl.

The accurate determination of vanadium, chromium, manganese, and iron in waters containing variable chloride and/or carbonate contents using the improved ICP–MS technique (Geo Labs method code IMW100) was tested through the analysis of certified reference materials (CRM) SLRS-2, SLRS-4 (river water; NRC-CNRC), NIST1643d (trace element in fresh water standard; NIST), TM-25, TM-Fscal, TM-Fwana, and TM-25/Lnglka (National Water Research Institute (NWRI) Interlaboratory QA Program, Study 79). The results of these analyses are shown in Figure 34.2 and Table 34.1. Because the concentrations of these elements were determined as part of the routine 3.5 minute analysis on the ICP–MS, during which data are obtained for over 50 major and trace elements, the values in Table 34.1 reflect the quality of data that can be produced during normal multi-elemental analysis. For more specific applications that require fewer elements, the amount of time spent analyzing each element can be increased, leading to better precision and reproducibility.

Although ammonia appears to efficiently remove argon- and chloride-based interferences on vanadium, chromium, manganese, and iron, it is unsuitable for the removal of the $ArCl^+$ and/or Ar_2^+ interferences on arsenic and selenium either as a result of its reaction with the analyte (arsenic) or its slower reaction rate with the Ar_2^+ ion (selenium). In order to overcome such interferences, alternative gases such as hydrogen and/or methane are required (Neubauer and Vollkopf 1999; Tanner, Baranov and Vollkopf 2000). Such methods are the focus of continuing work on the analysis of waters at Geo Labs.

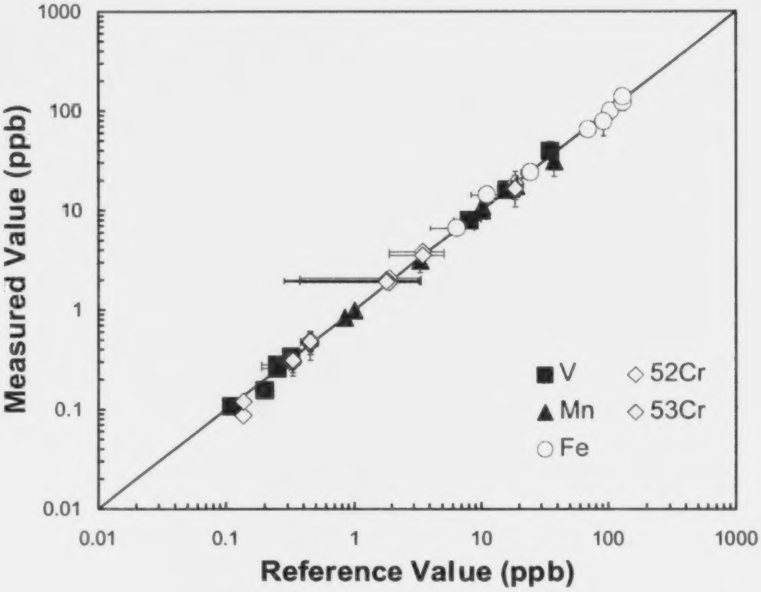

Figure 34.2. Vanadium, chromium, manganese, and iron contents determined in certified water reference materials by ICP–DRC–MS. Error bars indicate 95% confidence intervals on the mean (SLRS-2, SLRS-4, NIST 1643d) or the acceptable difference from the reference value (NWRI waters).

Table 34.1. Concentrations and recoveries of vanadium, chromium, manganese, and iron in water samples measured by ICP–DRC–MS.

		Reference Values	Measured Values		Recovery	
V						
SLRS-4	n=41	0.32 ± 0.03	0.34 ± 0.07		106 ± 22%	
SLRS-2	n=13	0.25 ± 0.06	0.26 ± 0.04		103 ± 15%	
	n=4	0.25 ± 0.06	0.28 ± 0.05[a]		113 ± 18%	
NIST 1643d	n=10	35.10 ± 1.40	39.4 ± 9.8		112 ± 28%	
TM-25	n=3	15.80 ± 2.36	16.1 ± 1.6		102 ± 10%	
TM-Fscal	n=3	0.11	0.108 ± 0.011		98 ± 10%	
TM-Fwana	n=3	0.20	0.156 ± 0.011		78 ± 6%	
TM-25/Lnglka	n=2	8.00 ± 1.89	8.00 ± 0.12		100 ± 2%	
Cr						
SLRS-4	n=39	0.33 ± 0.02	0.30 ± 0.06[b]	0.31 ± 0.09[c]	90 ± 19%	94 ± 28%
SLRS-2	n=13	0.45 ± 0.07	0.46 ± 0.10[b]	0.46 ± 0.14[c]	103 ± 23%	101 ± 32%
	n=4	0.45 ± 0.07	0.49 ± 0.11[ab]	0.48 ± 0.12[ac]	110 ± 25%	107 ± 28%
NIST 1643d	n=10	18.53 ± 0.20	18.80 ± 5.93[b]	16.60 ± 5.73[c]	101 ± 32%	90 ± 31%
TM-25	n=3	3.52 ± 1.62	3.83 ± 0.41[b]	3.54 ± 0.31[c]	109 ± 12%	100 ± 9%
TM-Fscal	n=3	0.14	0.087 ± 0.011[b]	0.119 ± 0.012[c]	63 ± 8%	87 ± 9%
TM-Fwana	n=3	1.90 ± 1.52	2.08 ± 0.20[b]	1.89 ± 0.19[c]	109 ± 11%	99 ± 10%
TM-25/Lnglka	n=2	1.80 ± 1.52	1.98 ± 0.02[b]	1.92 ± 0.03[c]	110 ± 1%	107 ± 2%
Mn						
SLRS-4	n=20	3.37 ± 0.18	3.14 ± 0.77		93 ± 23%	
SLRS-2	n=13	10.1 ± 0.3	10.0 ± 1.8		99 ± 18%	
	n=4	10.1 ± 0.3	11.0 ± 1.3[a]		109 ± 13%	
NIST 1643d	n=10	37.66 ± 0.83	31.13 ± 9.21		83 ± 24%	
TM-25	n=3	18.90 ± 2.54	17.64 ± 1.39		93 ± 7%	
TM-Fscal	n=3	0.84	0.84 ± 0.04		100 ± 5%	
TM-Fwana	n=3	1.00	0.99 ± 0.06		99 ± 6%	
TM-25/Lnglka	n=2	17.38 ± 2.45	16.57 ± 1.26		95 ± 7%	
Fe						
SLRS-4	n=41	103 ± 5	100 ± 19		97 ± 18%	
SLRS-2	n=13	129 ± 7	121 ± 21[a]		94 ± 16%	
	n=4	129 ± 7	138 ± 26		107 ± 20%	
NIST 1643d	n=10	91.2 ± 3.9	77.6 ± 21.7		85 ± 24%	
TM-25	n=3	11.0 ± 2.7	14.3 ± 1.1		130 ± 10%	
TM-Fscal	n=3	6.4 ± 2.4	6.6 ± 0.2		103 ± 3%	
TM-Fwana	n=3	24.4 ± 3.8	23.9 ± 1.5		98 ± 6%	
TM-25/Lnglka	n=2	68.9 ± 7.4	64.6 ± 3.9		94 ± 6%	

[a] SLRS-2 spiked with 1% HCl.

[b] Measured using ^{52}Cr.

[c] Measured using ^{53}Cr.

Rare Earth Elements

The improved sensitivity of water analyses on the ELAN 6100DRC in standard mode may be demonstrated by data recently obtained at Geo Labs for the rare earth elements (REE) in the natural river water certified material SLRS-4. Because a) this material was prepared from river water that was collected from the Ottawa River near the Chenaux generating station, Ontario, b) the REE composition of this material have been determined by a number of other laboratories (Yeghicheyan et al. 2001), and c) its REE concentrations range from approximately 0.5 ppb (e.g., light rare-earth elements (LREE): La, Ce, and Nd) to less than 1 ppt (e.g., heavy rare-earth elements (HREE): Dy, Ho, Er, Tm, Yb, and Lu), and experience a number of different interferences (as described above), it demonstrates both the accuracy and precision attainable in standard mode for elements at extremely low concentrations in typical water from the Canadian Shield. The results of the analyses are shown in Figure 34.3 and Table 34.2.

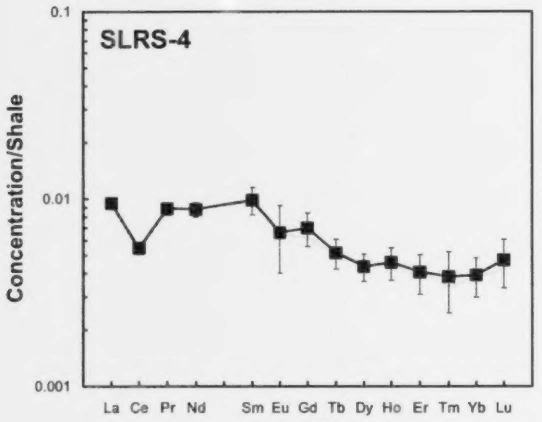

Figure 34.3. Shale-normalized REE plot for SLRS-4 analyzed at Geo Labs. Black line: mean of 38 analyses (error bars reflect 95% confidence intervals on the mean). Grey line: literature values *from* Yeghicheyan et al. (2001). Data normalized to North American Shale Composite (NASC) values *from* Gromet et al. (1984), with additional data *from* Haskin et al. (1968).

Table 34.2. REE concentrations determined in river water CRM SLRS-4 (n=38).

	Measured Value	Reference Value[a]
La	294 ± 21	287 ± 16
Ce	366 ± 27	360 ± 24
Pr	70.1 ± 5.4	69 ± 4
Nd	267 ± 23	269 ± 28
Sm	59 ± 10	57.4 ± 5.6
Eu	8.3 ± 3.2	8.0 ± 1.2
Gd	38 ± 8	34 ± 4
Tb	4.4 ± 0.8	4.3 ± 0.8
Dy	24.1 ± 4.0	24.2 ± 3.2
Ho	4.8 ± 0.9	4.7 ± 0.6
Er	13.3 ± 3.2	13.4 ± 1.2
Tm	1.9 ± 0.7	1.7 ± 0.4
Yb	12.2 ± 2.9	12.0 ± 0.8
Lu	2.1 ± 0.6	1.9 ± 0.2

[a] Yeghicheyan et al. (2001)
All concentrations in ppt (ng/L). Errors indicate 2 standard deviations on the mean.

Revised Detection Limits for Waters

The revised upper and lower limits for the analysis of fresh waters were calculated using duplicate analytical results for 115 samples analyzed during November and December 2001 (employing the method *from* Thompson and Howarth (1976) for data reduction) and an estimate of the concentration required to saturate the detector in pulse-counting mode. The results are presented in Table 34.3. Owing to the higher sensitivity of the new instrumentation, the major cation (magnesium and calcium) compositions of many lake and river samples may be either close to or above the upper limits by the new technique, resulting in poorer accuracy, and are probably better carried out by ICP–AES (Geo Labs method code IAW100).

Table 34.3. Revised operating range for trace element analyses of waters by ICP–DRC–MS (concentrations in ppb).

	Previous Lower Limit	Revised Lower Limit	Revised Upper Limit
Li	0.02	0.02	2000
Be	0.02	0.008	6000
Mg	15	50	4000
Al	0.2	0.1	350
Si	N.A.	60	3000
Ca	60	200	200,000
Sc	0.01	0.06	200
Ti	0.01	0.001	1500
V	0.01	0.03	175
Cr	0.03	0.004	120
Mn	0.2	0.08	150
Fe	1	0.4	1700
Co	0.02	0.006	200
Ni	0.4	0.08	1200
Cu	0.2	0.06	1000
Zn	0.5	0.1	1500
Ga	0.3	0.001	300
As	N.A.	0.04	1500
Rb	0.02	0.07	150
Sr	1	2	1000
Y	0.001	0.003	900
Zr	0.1	0.004	300
Nb	0.02	0.0008	125
Mo	0.3	0.005	800
Ag	0.05	0.03	225
Sn	0.02	0.004	300
Sb	0.03	0.003	400
Cs	0.005	0.0003	80
Ba	0.3	0.03	1250
La	0.001	0.001	90
Ce	0.001	0.0002	100
Pr	0.001	0.0003	80
Nd	0.003	0.004	650
Sm	0.001	0.002	550
Eu	0.001	0.0007	200
Gd	0.001	0.001	550
Tb	0.001	0.0004	110
Dy	0.001	0.001	450
Ho	0.001	0.003	125
Er	0.001	0.001	600
Tm	0.001	0.0003	140
Yb	0.001	0.0008	450
Lu	0.001	0.0003	160
Hf	0.1	0.001	900
Ta	0.02	0.0004	225
W	0.1	0.0007	800
Au	0.01	0.01	5000
Tl	0.01	0.0002	180
Pb	0.01	0.002	225
Bi	N.A.	0.0005	200
Th	0.02	0.001	175
U	0.001	0.0007	130

N.A.: Not analyzed.

SUMMARY

The trace metal compositions of waters, in particular their base-metal contents, have been shown to be important for mineral exploration, environmental monitoring, and geochemical mapping. However, the analysis of such samples has historically been hampered by the low concentrations of many of the elements of interest and the presence of interferences during ICP–MS analysis, leading to inaccurate and/or imprecise results. Methods for the analysis of water samples at the Geo Labs have recently been improved by the introduction of more sensitive instrumentation and the application of new technology, leading to lower detection limits for almost all elements and significant improvements in the determination of previously difficult to analyze elements. To date, the work on the elimination of problematic interferences has focussed on those that affect the determination of vanadium, chromium, manganese, and iron. Similar work on the improvement of arsenic and selenium analyses in waters will be carried out in the coming year. Owing to the higher sensitivity of the new instrumentation, routine major element analyses using ICP–DRC–MS have proved to be less accurate than by ICP–AES. Consequently, water analyses continue to be carried out by both ICP–AES (for major and trace elements, with or without ultrasonic nebulization) and ICP–MS (trace end ultra-trace elements) instruments, depending on the data required.

Further details of analytical services and methods available at Geo Labs may be obtained by contacting the Client Services Representative at 933 Ramsey Lake Rd., Sudbury, ON P3E 6B5. Tel: (705) 670 5637; toll free: 1-866-436-5227; e-mail: geoscience.labs@ndm.gov.on.ca; web site http://www.mndm.gov.on.ca/mndm/mines/labs/labintroe.htm.

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35. Precious Metal Analysis at the Geoscience Laboratories: Results from the New Low-Level Analytical Facility

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INTRODUCTION

Over the last quarter of a century, numerous geochemical studies have demonstrated the importance of accurate analyses of the platinum group elements (PGE: Os, Ir, Ru, Rh, Pt, and Pd) and gold (Au) at very low levels. Applications for which such analyses have been of critical importance include studies of early Earth history (e.g., Morgan 1986), meteorite impact events (e.g., Evans et al. 1993; Evans and Chai 1997), the production and evolution of mantle-derived magmas (e.g., Naldrett and Barnes 1986; Keays 1995), and the release of precious metals into the environment from automotive catalytic converters (e.g., Zereini and Friedrich 1999). However, nowhere has the influence of such analyses been more important than in the study of and exploration for base and precious metal mineralization (e.g., Naldrett et al. 1996; Naldrett et al. 1999).

Owing to the low abundance of the precious metals in most geological samples, their commonly heterogeneous distribution and frequent presence in acid-resistant mineral phases, most routine methods for their analysis employ aggressive techniques that pre-concentrate the elements from a large amount of sample material. The classic approach to precious metal analysis (lead fire-assay) involves the fusion of a large mass of sample in the presence of a molten lead collector, into which the metals are concentrated. Although this technique efficiently extracts the PGE and gold from most sample types, during subsequent processing of the lead button, many of the rarer precious metals (e.g., Os, Ir, Ru, and Rh) may be lost owing to volatilization or the formation of insoluble intermetallic compounds (Hall, Pelchat and Caughlin 1995). A more comprehensive fire-assay procedure uses a nickel sulphide (NiS) collector to pre-concentrate the precious metals (Robert, Van Wyk and Palmer 1971). In contrast to the lead-based technique, all 6 of the PGE, as well as gold, are recovered during the fusion and brought into solution for analysis. Because the NiS technique is relatively labour intensive, it is generally more costly than the lead-based technique, but the greater cost may be justified by the broader suite of elements determined and the lower detection limits available. For this reason, the NiS fusion technique remains the benchmark for routine assays.

To meet the growing needs of the geological community, a dedicated NiS fire-assay facility has been established at the Geoscience Laboratories (Geo Labs). The goal of this facility is to provide research-grade data for gold and PGE in geological samples. This paper will summarize the performance of the new facility and address some of the problems that may arise during analysis of particular sample types.

NICKEL SULPHIDE FIRE-ASSAY

The Geo Labs NiS fire-assay facility was originally established as a joint project with Laurentian University in 1995 under the leadership of Dr. R.R. Keays. During this time, it was predominantly used for collaborative projects that required research quality data at low concentrations. In 2001, management

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Summary of Field Work and Other Activities 2002.
Ontario Geological Survey, Open File Report 6100, p.35-1 to 35-5.

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of the facility was assumed by the Geo Labs and it has recently expanded into a dedicated work area that allows both a higher sample throughput and lower detection limits.

Most samples analyzed at the Geo Labs PGE facility are received as powders and are assumed to be homogenous at the 10 to 20 g level. Because the homogeneity of a sample depends on the particle size of the sample after crushing, the size of the mineral(s) that host the element of interest (e.g., PGE or gold) and the concentration(s) of each element in the mineral(s), all 3 factors need to be considered when preparing samples for submission. Pulverizing to smaller than 74 µm (–200 mesh) appears to be adequate for most sample types. However, samples containing high concentrations of precious metals and/or discrete PGE-bearing phases may require special treatment.

The NiS fire-assay technique employed by the Geo Labs is similar to that described by Shazali, Van't Dack and Gijbels (1987) and Jackson et al. (1990). A 15 g sample is fused with sodium carbonate and sodium tetraborate in the presence of nickel and sulphur, which form the collector phase. During fusion, unwanted lithophile elements from the sample are confined to the borosilicate slag, whereas the chalcophile precious metals are strongly partitioned into the NiS collector.

Nickel-sulphide buttons produced by the fire-assay process are transferred to Teflon™ digestion vessels for treatment with concentrated hydrochloric acid (HCl). Because the NiS matrix of the beads is readily soluble in HCl, whereas the precious metal component is largely insoluble, dissolution of the buttons efficiently concentrates the precious metals into a small mass of residue. However, because small amounts of the precious metals do dissolve in the acid, a tellurium coprecipitation stage is required to recover the dissolved metals so as to achieve maximum recovery. Following coprecipitation, solutions are vacuum filtered and the precipitate is subsequently re-dissolved in aqua regia and brought to volume with deionized water. Final analysis is performed by inductively coupled plasma mass spectrometry (ICP–MS) using a Perkin–Elmer ELAN 5000.

Although all 6 PGE may be quantitatively recovered by the NiS fire-assay, the Geo Labs currently does not report data for osmium owing to its potential loss as a volatile oxide at the aqua regia re-dissolution stage.

PROBLEMATIC SAMPLES

Although the fusion procedure is sufficiently robust to allow treatment of most sample types without modification, a number of sample types have been identified that do not respond well to the standard procedure, resulting in excessively large buttons with poor solubility (e.g., base-metal sulphides: Paukert and Rubeska 1993), incomplete sample decomposition (e.g., chromite-rich samples: Asif and Parry 1990; Zereini, Skerstupp and Urban 1994) or poor separation of the button from the slag phase (e.g., carbon-rich samples). Such samples may require alternative fluxes (e.g., substitution of lithium-based fluxes), pre-roasting of the sample to remove carbon and sulphur, or adjustment of the fire-assay charge. Because modification of the method is required for such samples (and the modification depends on the sample composition), the base-metal, sulphur and/or carbon contents of potentially problematic samples are required prior to analysis. To facilitate accurate analyses, such samples should therefore be flagged during sample submission.

Problems can also arise for samples that are elevated in copper when final analysis is by ICP–MS. Copper is readily carried through both the fire-assay and tellurium coprecipitation stages and is, therefore, present in the final solutions. Upon introduction to the plasma, a significant amount of the copper will react to form $^{63}Cu^{40}Ar$, which directly overlaps the only mass of rhodium. Data affected by this interference are mathematically corrected using the measured copper intensity and the CuAr/Cu ratio determined in a "set-up" solution. However, at very high copper contents, the accuracy of the data corrected by this method is degraded. Work towards the chemical elimination of this interference during analysis is currently in progress at the Geo Labs using the Dynamic Reaction Cell™ developed by Perkin–Elmer SCIEX.

REFERENCE MATERIAL DATA

The capabilities of the NiS technique are shown in Table 35.1 and Figure 35.1 using replicate analyses of CANMET certified reference materials (CRM) and an in-house standard of komatiite. Although the Geo Labs NiS facility was established for the analysis of samples containing low precious metals contents, it is clear that higher concentrations can be accommodated.

Table 35.1. Reference material data for the Geo Labs NiS fire-assay technique (concentrations in ppb).

	n	Ru	Rh	Pd	Ir	Pt	Au
TDB-1	20	0.26 ± 0.1	0.45 ± 0.1	22.1 ± 1.8	0.07 ± 0.03	4.8 ± 0.7	6.2 ± 0.6
Reference value		*0.3*	*0.7*	**22.4 ± 1.4**	*0.15*	**5.8 ± 1.1**	**6.3 ± 1**
WPR-1	10	21.2 ± 1	13.3 ± 1.0	235 ± 16	15.1 ± 0.7	277 ± 18	39.6 ± 6
Reference value		**22 ± 4**	**13.4 ± 0.9**	**235 ± 9**	**13.5 ± 1.8**	**285 ± 12**	**42 ± 3**
WGB-1	9	0.22 ± 0.1	0.20 ± 0.03	13 ± 2.3	0.20 ± 0.04	4.7 ± 1.0	2.4 ± 1.3
Reference value		*0.3*	*0.32*	**13.9 ± 2.1**	*0.33*	**6.1 ± 1.6**	**2.9 ± 1.1**
WMG-1	8	29 ± 3	28 ± 2	372 ± 39	49 ± 5	717 ± 87	97 ± 14
Reference value		**35 ± 5**	**26 ± 2**	**382 ± 13**	**46 ± 4**	**731 ± 35**	**110 ± 11**
OKUM*	6	4.1 ± 0.3	1.4 ± 0.1	11.4 ± 0.8	0.96 ± 0.08	11.0 ± 1.1	1.4 ± 0.4

Bold text: certified values with 95% confidence interval. **Italic text:** provisional values.* "in-house" reference material for which no certified data are available. ***n*:** number of replicate analyses.

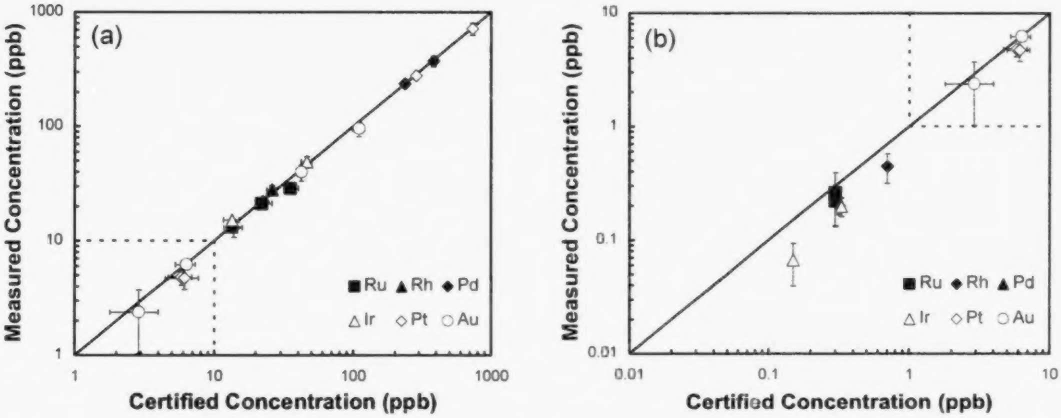

Figure 35.1. Comparison of Geo Labs NiS fire-assay data with certified values in reference materials. a) Normal working range of Geo Labs NiS fire-assay facility, where recommended concentrations, with errors, are available for CRM. b) Extension of plot to low concentrations where CRM possess only provisional concentrations with no estimates of precision and the analyses approach the lower limit of detection. Error bars: 95% confidence limits on mean values. Dashed boxes: area of overlap between figures. Straight lines represent perfect agreement between measured and reference values.

Table 35.2. Working ranges for the NiS fire-assay at the Geo Labs.

Element		Range	
		Lower Limit (ppb)	Upper Limit (ppb)
Gold	Au	0.27	1300
Platinum	Pt	0.10	1500
Palladium	Pd	0.06	1000
Rhodium	Rh	0.03	300
Ruthenium	Ru	0.09	1200
Iridium	Ir	0.03	2000

Assumed sample weight: 15g

ANALYTICAL WORKING RANGE

Routine upper and lower limits for the NiS fire-assay technique are presented in Table 35.2. The lower limit (LL) reflects the reproducibility of procedural blanks, whereas the upper limit (UL) represents the concentration at which the instrument detector approaches saturation. The capabilities of the low-level facility are maintained by ensuring that samples expected to contain high gold or PGE concentrations are not processed in the same environment as their low-level counterparts. As such, samples expected to contain in excess of 500 ppb of any individual precious metal (or 100 ppb Rh) should be flagged during submission. Although samples containing higher concentrations can be accommodated by dilution of the sample solution prior to analysis, the NiS fire-assay facility was not established with such samples in mind and the resulting data may be outside the validated working range.

FUTURE WORK

The Geo Labs low-level PGE facility is committed to continued improvement in services through optimization of existing procedures and the development of novel analytical techniques. Work in progress includes the removal of unwanted spectroscopic interferences by Dynamic Reaction Cell™ (DRC) ICP–MS and the rapid analysis of small sample sizes by a Na_2O_2 sinter method. Progress on these techniques will be discussed in future reports.

SUMMARY

Nickel sulphide fire-assay remains the benchmark for the routine determination of gold and PGE in geological materials. Results from the new PGE facility suggest that the Geo Labs can meet or exceed the needs of most low-level precious metals studies. Future developments aim to improve capabilities for small and/or problematic samples.

Further details of analytical services and methods available at Geo Labs may be obtained by contacting the Client Services Representative at 933 Ramsey Lake Rd., Sudbury, ON P3E 6B5. Tel: (705) 670 5637; toll free: 1-866-436-5227; e-mail: geoscience.labs@ndm.gov.on.ca; web site http://www.mndm.gov.on.ca/mndm/mines/labs/labintroe.htm.

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36. Mineralogical Controls on the Determination of Trace Elements Following Mixed Acid Dissolution

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INTRODUCTION

Over the last twenty years, accurate and precise analyses of trace elements in geological samples have become increasingly important in petrogenetic, metallogenetic and tectonic studies. Advances in analytical technology, in particular the advent of inductively coupled plasma mass spectrometry (ICP–MS), have permitted the simultaneous analysis of up to 60 elements in a wide range of sample types at part per billion concentrations. However, before a sample can normally be analyzed by ICP–MS (or other instrumental techniques that require the samples to be in solution, such as inductively coupled plasma atomic emission spectrometry (ICP–AES) or atomic absorption spectrometry (AAS)), it is necessary to decompose the sample efficiently so that the elements of interest are quantitatively recovered.

The most commonly used method of sample decomposition is acid dissolution using a mixture of inorganic acids to dissolve the constituent minerals (a summary of which is included in Chao and Sanzalone 1992). However, alternative methods, such as alkali fusions followed by dissolution of the molten sample in dilute acid (Crock and Lichte 1982; Potts 1987), or sintering with sodium peroxide followed by dissolution of the resulting mixture in either deionized water or dilute acid (Robinson, Higgins and Jenner 1986; Longerich et al. 1990), are also routinely used. Because mineral acids can be made considerably cleaner than the reagents used by other sample preparation techniques and introduce fewer salts into the sample solutions, the detection limits for many elements in samples prepared by acid dissolution may be considerably lower than those obtainable by other techniques and, consequently, the method is applicable to the simultaneous analysis of a wider range of elements. However, it has been shown that, under certain conditions, elements may either not be brought into solution by the acids owing to the presence of resistant mineral phases, or be lost from solution by precipitation or evaporation of volatile phases. When selecting a method for analysis or interpreting data produced by a particular technique, due diligence is therefore required in order to ensure that the resulting data accurately reflect the sample composition or that any anomalous data that result from analytical difficulties are correctly interpreted.

This report describes some recent work at the Geoscience Laboratories (Geo Labs) to investigate the mineralogical controls on the determination of trace elements in geological samples prepared by 2 mixed acid digestion techniques (the OT4, "open beaker" digestion and CT4, "closed beaker" techniques). The 2 techniques are identical with respect to the acids used, and each produces solutions that can be analyzed for the full suite of major and trace elements (Geo Labs method code IM100) or only the lithophile trace elements (Geo Labs method code IM101). However, the techniques differ significantly in the aggressiveness of their initial acid attack. Whereas the initial stage of the open-beaker technique is performed on a hot plate overnight, the closed-beaker technique starts with a week-long digestion in an enclosed, pressure-tight vessel after which the contents are transferred to an open beaker and processed as per the open-beaker technique. The open-beaker digestions take significantly less time to perform (typically 4 to 7 working days turn-around time), but may incompletely dissolve many acid-resistant

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mineral phases and, so, fail to give quantitative data for the associated trace elements (Walsh, Buckley and Barker 1981). In contrast, the closed-beaker digestions take longer to perform (typically 10 to 16 days), but the longer duration of the initial stage and the increased pressure and temperature during the digestion dissolves a greater range of minerals, resulting in a more complete analysis (French and Adams 1973; Tomlinson, Bowins and Hechler 1999).

EXPERIMENT

A suite of 10 certified reference materials (CRM) was digested using both the open- and closed-beaker digestion methods and the solutions analyzed for over 50 elements by ICP–AES (Geo Labs method code IA100) and ICP–MS (Geo Labs method codes IM100, and IM101). The selected CRM were either known to contain potentially acid-resistant minerals or were characterized by high abundances of elements that concentrate in such minerals. The suite included BX-N (bauxite; ANRT[1]), GSD-11 and GSD-12 (Chinese stream sediments; IGGE), GXR-1 (jasperoid "reef", USGS), GXR-3 (W-deposit; USGS), JP-1 (peridotite; GSJ), MAG-1 (marine mud; USGS), MA-N (granite; GIT-IWG), MRG-1 (gabbro; CCRMP), and SY-4 (syenite; CCRMP). Any visible residues after sample dissolution were investigated using energy dispersive spectrometry (EDS) on a scanning electron microscope (SEM).

The analysis of CRM permitted the comparison of the data obtained by the 2 digestion methods with the certified values. Although the resulting data allowed the determination of which elements were incompletely accessed by each technique (which would not be possible for normal uncharacterized samples), the use of CRM did place a number of limitations on the experiment. In particular,

1. Most CRM are prepared from unmetamorphosed igneous or sedimentary rocks and the constituent phases are relatively fresh and limited to magmatic or detrital minerals, or glass. As a consequence, potentially acid-resistant recrystallized or metamorphogenic minerals (e.g., garnet, staurolite, corundum or aluminosilicate (kyanite, sillimanite, and andalusite)) are rarely present and the existing minerals may be more easily digested than their recrystallized forms,
2. CRM are generally ground and sieved to yield powders that are significantly finer than most routine geochemical samples, so should not only dissolve more easily, but also yield finer residues that are more difficult to analyze,
3. If a trace element in a CRM is controlled by acid-resistant phases that lead to variable recoveries, the concentration of the element is often either poorly constrained or omitted from the certificate, so cannot be used for comparison.

Notwithstanding these problems, the results of the experiments clearly indicated that the concentrations determined in a number of sample types are affected by the minerals present and the preparation methods that were used.

DIGESTION METHODS

Both the open-beaker (OT4) and closed-beaker (CT4) digestion techniques used in the study employed a similar sequence of inorganic acid mixtures alternating with acid evaporation in order to ensure full sample decomposition. Initial sample decomposition was carried out using a mixture of concentrated hydrofluoric acid with lesser amounts of hydrochloric and perchloric acids. During this stage, most silicate minerals should have been broken down as the silicon reacted to form volatile SiF_4, which was removed by evaporation. The removal of silicon not only reduced the amount of total dissolved solids prior to analysis, but also resulted in more stable solutions by avoiding precipitation as a result of hydrolysis of silicon in solution. For the open-beaker digestions, the initial sample decompositions were carried out in open Teflon™ beakers on a hot plate in a well-ventilated fumehood. Although the addition of hydrochloric and perchloric acids increased the boiling point of the solution, as well as helping to further decompose the sample, the samples were effectively only exposed to the full strength of the acids for a few hours and evaporated to incipient dryness within 24 to 48 hours. For the closed-beaker digestions, the initial decomposition was carried out in closed screw-cap Savillex® Teflon™ bombs. Because the closed-beaker digestions did not permit the acid mixture to be boiled off, it was continuously refluxed within the container, thereby exposing the sample to hot acids over a longer period of time (typically 7 days achieves optimum decomposition) before being evaporated to dryness in an open beaker.

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[1] CRM issuing bodies: ANRT: Association Nationale de la Recherche Technique, Paris. IGGE: Institute of Geophysical and Geochemical Prospecting, People's Republic of China. USGS: United Sates Geological Survey. GSJ: Geological Survey of Japan. GIT-IWG: Groupe International de Travail – International Working Group. CCRMP: Canadian Certified Reference Material Project.

Once the acids employed during the first stage of each set of digestions had been evaporated off, a second acid mixture containing dilute hydrochloric and perchloric acids was added to the open beaker and the beakers returned to the hot plate. The addition of the dilute acids further decomposed the samples and ensured that any excess hydrofluoric acid from the first stage had been fumed off. After evaporating to dryness again, what remained of the samples was digested using a third and final acid mixture containing concentrated nitric and hydrochloric acids. The solutions were then heated and brought up to volume with dilute nitric acid. This last stage should have dissolved any remnants of the original sample and most precipitates that may have formed during the earlier evaporation stage, and converted the sample into a form that may be analyzed by AAS, ICP–AES, or ICP–MS.

RESULTS OF DIGESTIONS

The results of the analysis of the 10 CRMs are shown in Table 36.1. Although data for many of the elements were obtained using more than one technique or calibration method, only 1 representative value is presented for each element in each sample. The majority of the data were obtained by ICP–MS, with calibration against a set of 3 well-characterized reference materials (Geo Labs method code IM100). However, data obtained by ICP-MS with calibration against synthetic standard solutions (Geo Labs method code IM101) are presented for samples containing low abundances of lutetium, strontium, tantalum, and thulium. Where there is an overlap between analytical methods, the data obtained by each technique are consistent and show similar differences between the solutions produced by the 2 digestion procedures.

The concentrations of many of elements (e.g., most of the transition metals (Sc, V, Mn, Fe, Co, Ni, Cu, and Zn), large ion lithophile elements (LILE: Rb, Sr, Cs, Ba, and Pb), light rare earth elements (LREE: La, Ce, Pr, Nd, Sm, and Eu) and semi-metallic elements (e.g., Cd, Sb, Tl, and Bi)), show no systematic difference between the data obtained for each of the digestion methods. However, the concentrations of a number of elements in certain samples are consistently low in the solutions produced by open-beaker digestions relative to both the certified values for the materials and/or the results for the closed-beaker digestions. The most striking differences are observed for chromium, the heavy rare earth elements (HREE: Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), high field strength elements (HFSE: e.g., Y, Zr, Hf) and tin (Figure 36.1). For these elements, the analyses may be up to 90% too low in some samples (e.g., Sn in MA-N and Zr in SY-4). It has previously been shown that zircon may be incompletely digested by the open-beaker technique used at Geo Labs (Tomlinson, Bowins and Hechler 1999). However, it is clear that not only are other minerals not adequately attacked by the open-beaker technique, but that even the closed-beaker digestion may be incapable of digesting certain phases and even more aggressive methods may be required.

Table 36.1. Compilation of results for the analysis of major and trace elements in CRM sample suite.

	BX-N			GSD-11			GSD-12			GXR-1			GXR-3		
	OT4	CT4	Ref.	OT4	CT4	Ref.	OT4	CT4	Ref.	OT4	CT4	Ref.	OT4	CT4	Ref.
Al (wt %)	28.15	26.18	28.69	5.43	6.7	5.49	4.96	6.31	4.92	***0.76***	*3.03*	*3.51*	***3.12***	*6.52*	*6.4*
Ba	29.8	26.8	30	236.3	229.0	260	196.3	183.2	206	*667*	*693*	*750*	*5307*	*4962†*	*5000*
Be	6.39	4.92	5.5	22.7	18.0	26	7.89	6.57	8.2	*1.04*	*1.36*	*1.22*	*28.9*	*21.1*	*26*
Bi	*2.6*	*1.9*	*1.7*	71	57†	50	15.6	11.8	10.9	*OS*	*OS*	*1380*	-	*0.15*	*(16)*
Ca (wt %)	0.29	0.15	0.12	0.42	0.33	0.34	0.92	0.82	0.83	*0.85*	*0.91*	*0.96*	*13.73*	*13.67*	*13.58*
Cd	0.6	0.1		3.35	2.36	2.3	6.6	4.6	4	*4.29*	*2.75*	*3.3*	*0.60*	*0.37*	*(1.8)*
Ce	458	514	520	40.4	61.0	58	50.0	71.0	61	*9.8*	*13.5*	*17*	*10.7*	*14.6*	*18*
Co	36.6	33.6	30	8.01	8.20	8.5	8.12	8.23	8.8	*8.11*	*8.28*	*8.2*	*50.9*	*49.1*	*46*
Cr	240	283	280	31.3	46.8	40	25.6	42.1	35	*7.6*	*11.1*	*12*	*11.59*	*20.48*	*19.3*
Cs	*0.37*	*0.38*	*0.4*	18.01	18.86	17.4	8.28	8.38	7.9	*3.2*	*3.5*	*3*	*185.6*	*195.4*	*175*
Cu	17.7	21.5	18	80.36	82.50	78.6	1420	1303	1230	*1252*	*1184*	*1110*	*14.3*	*18.2*	*15*
Dy	17.35	18.25	18.5	**5.03**	7.32	7.2	**3.46**	4.65	4.8	*4.64*	*4.78*	*4.3*	*1.2*	*1.6*	
Er	10.7	10.8	11	**3.15**	4.47	4.6	**2.26**	3.01	3.1	*2.8*	*2.7*		*0.9*	*1.0*	
Eu	4.59	4.00	4.4	0.53	0.57	0.6	0.597	0.555	0.61	*0.706*	*0.717*	*0.69*	*0.784*	*1.390*	*0.48*
Fe (wt %)	15.04	18.01	16.21	2.71	3.68	3.07	3.11	4.01	3.41	*24*	*26.12*	*26.26*	*19.82*	*25*	*19.03*
Ga	62.2	59.9	67	17.33	16.98	18.5	12.66	13.38	14.1	***8.0***	*13.1*	*13.8*	***8.4***	*13.0*	*(18)*
Gd	19.8	19.1	20	5.23	5.87	5.9	4.09	4.34	4.4	*3.83*	*4.05*	*4.2*	*1.523*	*1.616*	*(2.35)*
Hf	***10.03***	*14.74*	*15.2*	**2.76**	4.79	5.4	**3.34**	7.56	8.3	*0.523*	*0.644*	*0.96*	*0.95*	*1.51*	*2.4*
Ho	3.82	3.83	4.1	**1.07**	1.53	1.4	**0.784**	0.986	0.94	*1.0*	*1.0*		*0.3*	*0.3*	
La	394.8†	367.7†	355	26.2	26.2	30	28.93	29.25	32.7	*7.05*	*7.33*	*7.5*	*7.72*	*7.67*	*8.8*
Li	*41.1*	*35.9*	*39*	84.36	59.72	70.6	47.8	31.4	39	*9.34*	*10.35*	*8.2*	*179.9*	*141.4*	*114*
Lu	1.63	1.71	1.8	**0.526**	0.784	0.78	***0.398***	*0.604*	*0.58*	*0.315*	*0.328*	*0.28*	*0.136*	*0.168*	*(0.17)*
Mg (wt %)	0.06	0.05	0.07	0.31	0.43	0.37	0.24	0.29	0.28	*0.18*	*0.22*	*0.22*	*0.71*	*0.99*	*0.81*
Mn (wt%)	0.03	0.03	0.04	0.17	0.2	0.25	0.1	0.11	0.14	*0.07*	*0.07*	*0.07*	*OS*	*OS*	*2.23*
Mo	10.65	9.07	8.3	7.46	7.32	5.9	10.51	10.05	8.4	*20.2*	*21.1*	*18*	*7.12*	*7.10*	*(6.6)*
Nb	52.3	53.9	52	21.1	25.3	25	13.05	14.73	15.4	*0.93*	*1.29*	*(0.8)*	*2.5*	*2.8*	*(44)*
Nd	175.0	162.7	163	24.7	24.9	27	24.12	24.30	25.6	*8.3*	*8.8*	*(18)*	*7.53*	*7.70*	*(8.3)*
Ni	194.3	171.1	180	15.28	16.40	14.4	14.26	14.10	12.8	*38.9*	*41.6*	*41*	*58.8*	*63.4*	*60*
P (wt %)	0.06	0.05		0.02	0.02	0.03	0.02	0.02	0.02	*0.06*	*0.06*	*0.07*	*0.11*	*0.12*	*0.11*
Pb	149.8	140.3	135	648	696	636	321.0	317.5	285	*838*	*OS*	*730*	*11.3*	*11.4*	*15*
Pr	60.8	57.4	54	6.79	6.54	7.4	6.87	6.70	6.9	*1.9*	*2.0*		*1.9*	*1.9*	
Rb	3.34	2.28	3.6	427.9	468.8	408	280.7	280.8	270	*2.9*	*3.0*	*(14)*	*104.8*	*97.5*	*92*
Sb	*5.2*	*8.0*	*8*	9.54	14.28	14.9	16.08	25.89	24.3	*67.2*	*128.1*	*122*	*26.1*	*38.5*	*38*
Sc	62.7	56.5	60	7.09	7.46	7.4	5.20	4.72	5.1	*1.64*	*1.29*	*1.58*	*19.70*	*18.51*	*16.8*
Sm	22.9	21.8	22	5.81	6.07	6.2	4.5	4.9	5	*2.78*	*3.00*	*2.7*	*1.52*	*1.60*	*1.3*
Sn	**4.46**	13.64	13.4	**55.6**	**66.5**	370	**20.0**	**22.7**	54	***19.4***	*53.4*	*54*	*0.44*	*0.69*	*(1.7)*
Sr	114.0	83.9	110	26.1	28.9	29	22.97	24.93	24.4	*295.8*	*274.5*	*275*	*1066*	*934*	*950*
Ta	**3.77**	4.48	4.6	6.41	6.62	5.7	**2.10**	3.26	3.2	*0.115‡*	*0.124‡*	*0.175*	*1.78‡*	*1.17‡*	*0.29*
Tb	3.2	3.1	3	**0.881**	1.080	1.13	**0.644**	0.717	0.82	*0.707*	*0.750*	*0.83*	*0.217*	*0.251*	*(0.24)*
Th	*53.7*	*48.9*	*50*	22.73	24.61	23.3	21.47	22.49	21.4	*2.542*	*2.562*	*2.44*	*1.866*	*2.135*	*2.94*
Ti (wt %)	**0.99**	**1.17**	1.42	**0.13**	**0.17**	0.21	**0.1**	**0.12**	0.15	*0.02*	*0.02*	*0.03*	*0.07*	*0.09*	*0.1*
Tl	0.2	0.1		3.23	3.40	2.9	1.97	2.05	1.8	*0.929*	*0.694*	*0.39*	*2.35*	*1.92*	*3.6*
Tm	1.67	1.89	1.7	**0.527**	0.818	0.74	**0.359**	0.571	0.53	*0.403*	*0.434*	*(0.43)*	*0.122*	*0.000*	*(0.19)*
U	*8.67*	*8.51*	*8.8*	9.48	9.92	9.1	7.81	8.80	7.8	*35.32*	*34.70*	*34.9*	*1.9*	*2.1*	*3*
V	*350.4*	*343.5*	*350*	38.22	43.67	46.8	43.33	43.37	46.6	*71.3*	*84.0*	*80*	*36.1*	*49.4*	*42*
W	*10.7*	*12.4*	*9*	110.3	107.7	126	*35.35*	*33.27*	*37.4*	*171.7*	*183.7*	*164*	*10159†*	*11100†*	*10700*
Y	110.2	121.0	114	**29.83**	48.04	42.7	**21.49**	32.79	29.3	*29.5*	*33.8*	*32*	*13.9*	*15.3*	*15*
Yb	11.35	11.32	11.6	**3.44**	5.08	5.1	**2.56**	3.61	3.7	*2.33*	*2.31*	*1.9*	*0.83*	*1.33*	*(0.91)*
Zn	83.9	84.6	80	365.9	328.3	373	478.3	454.9	498	*790*	*724*	*760*	*233.2*	*194.4*	*207*
Zr	**323.2**	548.2	550	**62.8**	146.4	153	**72.2**	228.6	234	*17.7*	*25.7*	*(38)*	*55.9*	*81.2*	*63*

Data obtained using Geo Labs method code IM100 unless otherwise stated. OT4: open-beaker digestions. CT4: closed-beaker digestions. Ref.: reference values. Concentrations in ppm (except Al, Ca, Fe, Mg, Mn, P, Ti: weight %). OS: above instrumental analytical range. N.D.: Not detected. **Bold:** anomalously low concentrations in test samples. *Italics:* only proposed or information (bracketed) values available for CRM. † Sample diluted 10 fold prior to analysis. ‡ Data obtained using method code IM101. Blank (no value) indicates a reference value is not available.

Table 36.1. Continued

		JP-1			MAG-1			MA-N			MRG-1			SY-4	
	OT4	**CT4**	**Ref.**	**OT4**	**CT4**	**Ref.**	**OT4**	**CT4**	**Ref.**	**OT4**	**CT4**	**Ref.**	**OT4**	**CT4**	**Ref.**
Al (wt %)	*0.24*	*0.37*	*0.33*	8.61	8.74	8.13	9.89	11.3	9.32	4.21	3.29	4.48	*11.31*	*10.86*	*11*
Ba	*9.1*	*9.6*	*17*	497	475	479	42.2	38.6	42	*50.2*	*47.9*	*61*	356	365	340
Be	*0.5*	*0.7*		3.60	3.12	3.2	315	221	300	*0.368*	*0.912*	*0.61*	2.9	2.82	2.6
Bi	*0.25*	*N.D.*		*1.72*	*N.D.*	*0.34*	N.D.	1.99		*0.316*	*N.D.*	*(0.13)*	*0.07*	*0.05*	*(0.17)*
Ca (wt %)	*0.53*	*0.37*	*0.4*	1.19	1.01	0.98	0.66	0.46	0.42	9.78	9.79	10.51	*6.19*	*5.55*	*5.8*
Cd	*0.1*	*N.D.*		0.357	0.215	0.202	3.0	1.7	2	*0.245*	*0.146*	*0.168*	*0.10*	*0.07*	*0.4*
Ce	*0.15*	*0.10*	*0.2*	78.4	82.5	88	0.95	0.71	0.9	*20.3*	*21.6*	*26*	124	122	122
Co	*104.4*	*110.5*	*116*	21.65	21.25	20.4	0.63	0.44	0.5	88.9	84.5	87	2.77	3.96	2.8
Cr	***633***	*3106†*	*2970*	100.0	108.0	97	3.8	4.0	3	***307***	*428.7*	*430*	11	12.7	12
Cs	*0.1*	*0.1*		9.73	9.85	8.6	678	615†	640	*0.767*	*0.733*	*0.57*	1.75	1.645	1.5
Cu	*8.80*	*11.16*	*5.7*	34.8	30.6	30	164.2	142.7	140	130.4	121.3	134	5.8	7.88	7
Dy	*0.019*	*0.020*	*0.02*	4.53	5.05	5.2	*0.067*	*0.045*	*0.07*	*2.93*	*2.90*	*2.9*	17.9	16.7	18.2
Er	*0.018*	*0.009*	*0.02*	*2.3*	*2.6*	*3*	*0.028*	*0.027*	*0.04*	*1.193*	*1.114*	*1.12*	13.87	12.4	14.2
Eu	*0.009*	*0.006*	*0.0073*	1.532	1.369	1.55	*0.025*	*0.022*	*0.02*	1.538	1.288	1.39	2	1.69	2
Fe (wt %)	*4.55*	*6.8*	*5.83*	*5.16*	*5.41*	*4.76*	0.34	0.41	0.33	12.29	12.04	12.55	5.26	5.01	4.34
Ga	*0.37*	*0.59*	*0.5*	22.92	21.86	20.4	58.2	57.4	59	*18.1*	*16.5*	*17*	34	33.41	
Gd	*0.021*	*0.012*	*0.02*	6.22	6.15	5.8	*0.102*	*0.056*	*0.08*	*4.3*	*3.9*	*4*	14.2	12.1	14
Hf	0.135	0.110	0.21	2.67	3.56	3.7	**3.1**	4.3	4.5	3.8	3.47	3.76	**1.59**	9.5	10.6
Ho				0.92	0.97	1.02	*0.01*	*0.009*	*0.017*	0.558	0.490	0.49	4.6	3.86	4.3
La	*0.05*	*0.06*	*0.1*	42.5	41.0	43	*0.63*	*0.40*	*0.5*	9.18	8.26	9.8	57.9	56	58
Li	*3.30*	*5.80*	*1.8*	85.4	77.1	79	5311	5440†	4900	*4.52*	*7.14*	*4.2*	39.4	39.6	37
Lu	*0.009‡*	*0.009‡*		0.34	0.40	0.4	*0.004*	*0.005*	*0.005*	*0.127*	*0.114*	*0.12*	2.06	1.72	2.1
Mg (wt %)	*22.45*	*30.39*	*26.97*	1.96	1.93	1.81	0.04	0.03	0.02	*6.65*	*6.66*	*8.17*	0.33	0.33	0.3
Mn (wt%)	*0.07*	*0.08*	*0.09*	0.06	0.06	0.08	0.02	0.02	0.03	0.09	0.1	0.13	0.07	0.07	0.08
Mo	*0.2*	*0.4*		*1.28*	*1.18*	*1.6*	*0.74*	*0.14*	*0.3*	0.990	1.248	0.87	*0.32*	*0.335*	*(0.77)*
Nb	*0.07*	*0.10*	*1.2*	*13.2*	*14.1*	*12*	200.4	231.1	173	*20.7*	*17.5*	*20*	15.2	14.79	13
Nd	*0.014*	*0.071*	*0.07*	38.9	38.2	38	*0.56*	*0.30*	*0.4*	19.08	17.71	19.2	59	54	57
Ni	*2820*	*2406*	*2460*	57.9	52.3	53	5.9	3.7	3	183.4	176.1	193	7.7	18	9
P (wt %)	*N.D.*	*0.01*		0.08	0.07	0.07	0.68	0.68	0.61	0.02	0.02	0.03	0.06	0.07	0.06
Pb	*0.327*	*0.383*	*0.114*	28.7	27.1	24	28.5	27.6	29	*5.5*	*5.1*	*10*	9.85	9.68	10
Pr	*0.016*	*0.014*	*0.02*	*10.67*	*10.08*	*9.3*	*0.13*	*0.08*	*0.1*	*4.10*	*3.56*	*3.4*	15.3	13.8	15
Rb	*0.5*	*0.9*		156.2	150.4	149	4551‡	3959†	3600	*7.54*	*7.32*	*8.5*	58.7	54.8	55
Sb	*N.D.*	*0.2*		0.65	1.18	0.96	1.06	1.79	1.7	*0.343*	*0.632*	*0.86*	*0.059*	*0.02*	*(0.055)*
Sc	6.79	6.77	7.07	18.18	17.49	17.2	1.31	N.D.	0.2	55.4	54.9	55	1.6	2.43	1.1
Sm	*0.026*	*0.010*	*0.02*	7.44	7.27	7.5	*0.076*	*0.075*	*0.09*	4.41	4.29	4.5	12.9	11.8	12.7
Sn	*0.045*	*0.057*	*0.05*	*3.37*	*3.41*	*3.6*	**80**	**111**	900	*3.76*	*3.96*	*(3.6)*	*7.6*	*7.62*	*7.1*
Sr	*0.646‡*	*0.003‡*		143.7	132.8	146	88.3	67.7	84	262.6	215.3	266	1247	1214	1191
Ta	*0.07‡*	*0.16‡*		*0.99‡*	*1.06‡*	*1.1*	233‡	229‡	290	1.03‡	0.89‡	0.8	0.88	0.91	0.9
Tb	*0.0040*	*0.0030*	*0.003*	0.923	0.909	0.96	*0.020*	*0.011*	*0.01*	0.637	0.547	0.51	2.67	2.17	2.6
Th	*0.028*	*0.044*	*0.18*	11.86	11.71	11.9	1.77	1.57	1.4	*0.780*	*0.663*	*0.93*	1.34	1.18	1.4
Ti (wt %)	*0.0022*	*0.0022*		0.34	0.37	0.45	0.01	0.01	0.01	1.72	1.76	2.26	*0.16*	*0.15*	*(0.17)*
Tl	*N.D.*	*N.D.*		*0.824*	*0.835*	*(0.59)*	*22.2*	*23.1*	*15*	*0.0590*	*0.0610*	*0.055*	*0.272*	*0.33*	*(0.3)*
Tm	*0.008‡*	*0.010‡*		0.352	0.439	0.43	*0.007*	*0.005*	*0.007*	*0.140*	*0.165*	*0.11*	2.22	2.2	2.3
U	*0.018*	*0.017*	*0.05*	2.73	2.71	2.7	13.38	12.52	12.5	*0.282*	*0.222*	*0.24*	0.75	0.82	0.8
V	*32.8*	*32.4*	*29*	144.3	138.9	140	*0.91*	*6.97*	*0.2*	510.5	492.2	526	14	26.1	8
W	*0.8*	*1.8*		*2.42*	*2.43*	*1.4*	70.9	63.2	70	*8.49*	*4.44*	*0.3*	*0.155*	*0.257*	*(1.7)*
Y	*0.1*	*0.1*		22.4	28.4	28	*0.34*	*0.38*	*0.4*	12.8	13.2	14	127	104	119
Yb	*0.015*	*0.015*	*0.02*	2.33	2.55	2.6	*0.099*	*0.033*	*0.04*	*0.85*	*0.84*	*(0.6)*	14.8	12.6	14.8
Zn	*29.20*	*41.68*	*29.5*	139.7	124.4	130	235.5	202.3	220	202.4	185.3	191	88.6	58	93
Zr	5.03	4.44	6.3	82.9	124.4	126	20.8	30.4	25	91.7	99.6	108	**84**	495	517

Data obtained using Geo Labs method code IM100 unless otherwise stated. OT4: open-beaker digestions, CT4: closed-beaker digestions. Ref.: reference values. Concentrations in ppm (except Al, Ca, Fe, Mg, Mn, P, Ti: weight %). OS: above instrumental analytical range. N.D.: Not detected. **Bold:** anomalously low concentrations in test samples. *Italics:* only proposed or information (bracketed) values available for CRM. † Sample diluted 10 fold prior to analysis. ‡ Data obtained using method code IM101. Blank (no value) indicates a reference value is not available.

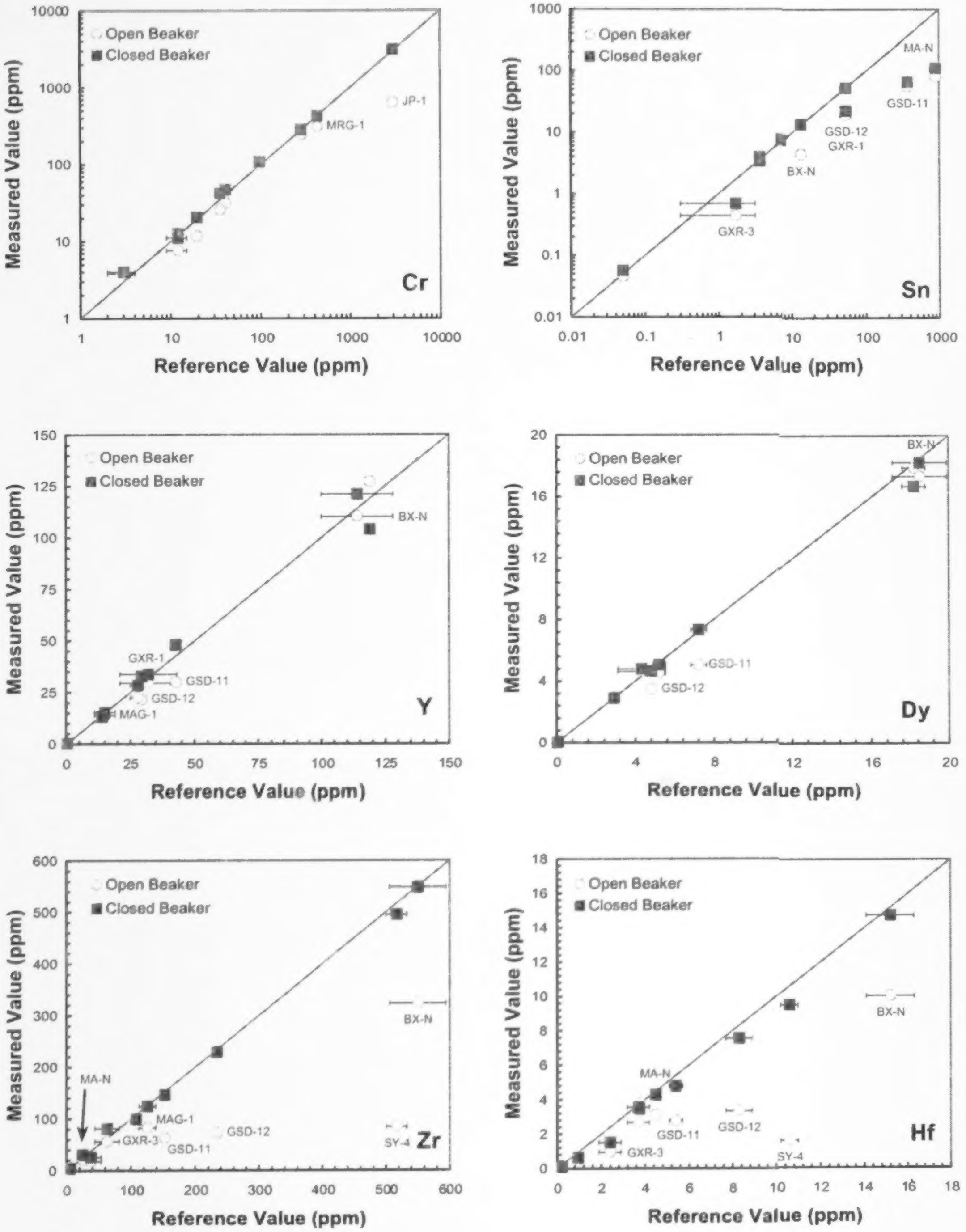

Figure 36.1. Plots of the measured concentrations as a function of reference values for selected trace elements in the suite of CRM analyzed during the study. Error bars indicate uncertainty in reference values. Full data are presented in Table 36.1. Samples with anomalously low concentrations in solutions prepared by the open-beaker technique are labelled.

ANALYSIS OF RESIDUES

In order to determine which minerals were responsible for the low recovery observed in the reference materials, the residues after digestion were separated by filtering through 0.45 μm nylon filter membranes and mounted in epoxy resin for scanning electron microscope (SEM) analysis. Energy-dispersive x-ray analysis was performed on the SEM in the Geo Labs using a 2 nA beam current, 20 kV accelerating voltage. Data reduction was carried out using the ZAF-4 correction procedure (Goldstein et al. 1992), with calibration against oxide standards for silicon, aluminum, chromium, iron, magnesium, titanium, and tin; cubic zircon for zirconium and yttrium; and Smithsonian REE phosphate standards for the REE and phosphorus. Owing to the low concentrations of hafnium in the zirconia standard and absence of a suitable standard for tungsten, it was not possible to calibrate all trace elements observed in the residues. Qualitative data for hafnium in zircon were obtained by comparison of the intensities of $L\alpha_1$ line in the samples with those in the cubic zirconia standard (1.2 weight % HfO_2).

The minerals observed in the residues are summarized in Table 36.2. The minerals may be divided into 3 groups: those composed primarily of major elements that contain low concentrations of trace elements and therefore do not contribute to any deficit in the analyses (e.g., quartz, topaz, diaspore, and carbonaceous material), those that contain one or more trace elements as structural components or in high concentrations and therefore can account for the low concentrations observed in some of the analyses (e.g., cassiterite, chromite, rutile, spinel, xenotime, and zircon), and those that were introduced during sample processing (e.g., alumina from the crushing media).

Cassiterite

Cassiterite has long been recognized to be resistant to acid attack under most conditions and to require fusion of the sample to ensure complete sample decomposition (Potts 1987). It was found in 3 of the 10 residues investigated (granite MA-N, and sediments GSD-11 and GSD-12). Whereas the grains from GSD-12 were found to contain negligible concentrations of other trace elements, those from GSD-11 and MA-N contained minor amounts of tantalum (GSD-11), or both tantalum and niobium (MA-N). The presence of cassiterite in the residues after the dissolution of MA-N, GSD-11, and GSD-12 accounts for the low concentrations of tin obtained for these materials after both open- and closed-beaker digestions (*see* Table 36.1; *see* Figure 36.1), and may account for the concentrations determined in the open-beaker digestions of GXR-1, GXR-3, and BX-N. However, because the concentrations of niobium and tantalum are not similarly depressed in GSD-11 and MA-N, it is unclear whether cassiterite is a significant host for HFSE in these samples.

Table 36.2. Minerals observed in residues after open-beaker digestion of CRM suite.

CRM	Mineral Observed	Formula	Trace Elements Found
BX-N	Diaspore	AlO(OH)	N.D.
	Quartz	SiO_2	N.D.
	Rutile	TiO_2	Ti
	Xenotime	YPO_4	Y, Gd, Dy, Er, Yb
	Zircon	$ZrSiO_4$	Zr, tr. Hf
GSD-11	Cassiterite	SnO_2	Sn, tr. Ta
	Rutile	TiO_2	Ti
	Topaz	$Al_2SiO_4(OH,F)_2$	N.D.
	Xenotime	YPO_4	Y, Gd, Dy, Er, Yb, U
	Zircon	$ZrSiO_4$	Zr, Y, Hf
GSD-12	Cassiterite	SnO_2	Sn
	Rutile	TiO_2	Ti
	Spinel	$MgAl_2O_4$	N.D.
	Topaz	$Al_2SiO_4(OH,F)_2$	N.D.
	Xenotime	YPO_4	Y, Gd, Dy, Er, Yb
	Zircon	$ZrSiO_4$	Zr
GXR-1	Alumina	Al_2O_3	N.D.
	Zircon	$ZrSiO_4$	Zr, tr. Y
GXR-3	Alumina	Al_2O_3	N.D.
	Zircon	$ZrSiO_4$	Zr, tr. Y, Hf
	Iron Tungstate	$FeWO_4$ or $FeWO_4 \cdot 4(H_2O)$	W
JP-1	Chromite	$(Mg, Fe)(Cr,Al)_2O_4$	Cr
MAG-1	Carbonaceous Material		N.D.
MA-N	Cassiterite	SnO_2	Sn, tr. Nb, Ta
	Topaz	$Al_2SiO_4(OH,F)_2$	N.D.
	Zircon	$ZrSiO_4$	Zr, Hf
MRG-1	Chromite	$(Mg, Fe)(Cr, Al)_2O_4$	Cr
SY-4	Diaspore	AlO(OH)	N.D.
	Zircon	$ZrSiO_4$	Zr, tr. Y

N.D. : No trace elements detected in mineral; tr. : trace.

Spinel and Chromite

Both spinel *sensu stricto* and chromite were found in the residues after open-beaker digestions (spinel in the Chinese sediment GSD-12; chromite in the peridotite JP-1 and gabbro MRG-1). Most of the chromite grains were subhedral and showed negligible evidence of attack by the acids (Photo 36.1A). The compositions of chromites ranged from $Mg^{\#} = 45$ to 62[2] and $Cr^{\#} = 40$ to 65[3] (JP-1) to $Mg^{\#} = 48$ to 56 and $Cr^{\#} = 75$ to 80 (MRG-1), and were consistent with the ranges expected for moderately depleted mantle peridotite and a reasonably rapidly cooled gabbroic rock formed from a magnesian magma. From the angular shapes of the mineral grains and apparently negligible change in mineral composition, chromite appears to be impervious to acid attack under open-beaker conditions. The chromites in JP-1 and MRG-1 were not found to contain any trace elements other than chromium. However, their presence in the samples and failure to dissolve under open-beaker conditions does account for the low chromium concentrations obtained for these materials using open-beaker digestions (*see* Table 36.1; *see* Figure 36.1). Because the results for the closed-beaker digestions are not similarly depressed, it is inferred that chromite is successfully digested by the closed-beaker technique.

The identification of magnesian spinel in the residue after the open-beaker digestion of GSD-12 confirms the general acid-insolubility of minerals of the spinel group (e.g., spinel, hercynite, magnetite, and chromite). However, because the principal components of spinel group minerals (Mg, Fe, and Al) are major elements in most samples, the insolubility of spinel group minerals only becomes significant at low concentrations of the individual trace elements and/or high abundances of the minerals (e.g., Al in spinel peridotites) or where magnesium and iron are replaced by less abundant elements (e.g., Zn, Mn, and/or Ni).

Rutile

Rutile was found in 3 of the 10 residues investigated (bauxite BX-N, and sediments GSD-11 and GSD-12). In BX-N, the mineral grains were generally present as inclusions in, or on the edges of undigested diaspore grains, where they appeared relatively fresh (Photo 36.1B). However, in GSD-11 and GSD-12, the grains were commonly pitted, either as a result of abrasion during sedimentary processes or partial digestion during the acid attack. Although rutile can contain appreciable amounts of niobium and/or tantalum, only minor amounts of iron (<0.5 weight % Fe) were found in addition to TiO_2 in the analyzed grains. The presence of rutile in samples BX-N, GSD-11, and GSD-12 may account for the marginally lower TiO_2 concentrations obtained for these materials (and possibly GXR-1 and GXR-3) after open-beaker digestions (*see* Table 36.1). However, the low concentrations determined for solutions produced by both dissolution methods, suggests that even the closed-beaker method may not digest rutile completely.

Xenotime

Xenotime was found in the same residues that contain rutile (bauxite BX-N and sediments GSD-11 and GSD-12), where it was present as both inclusions within other phases (e.g., diaspore in BX-N, Photo 36.1B) and discrete grains (all 3 samples). Owing to the small size of the grains (≤ 5 µm), it was not possible to determine whether the grains showed any evidence of acid attack. Analysis of the grains from all 3 samples showed them to be strongly enriched in HREE (Gd_2O_3 and Dy_2O_3 were quantified at 1.3 to 3.5 weight % and 3.8 to 7.4 weight %, respectively, and appreciable amounts of Er and Yb were also observed) and those from GSD-11 to contain minor amounts of uranium. Such compositions are consistent with literature values for the mineral, which suggest that it may also contain significant amounts of thorium, zirconium, and LREE (Palache, Berman and Frondel 1951). The presence of xenotime in samples BX-N, GSD-11, and GSD-12 may account for the low concentrations of yttrium and/or the HREE obtained for these materials (and possibly GXR-1, GXR-3, and MAG-1) after open-beaker digestions relative to both the results after closed-beaker digestions and the certified values for the reference materials (*see* Table 36.1; *see* Figure 36.1). Because the results for the closed-beaker digestions are not depressed in these samples, it is inferred that xenotime is successfully digested by the more aggressive closed-beaker technique. Further investigation is required in order to determine why the average concentration determined for SY-4 by open-beaker digestion is higher than that obtained by the closed-beaker method.

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[2] $Mg^{\#}$ = atomic Mg/(Mg+Fe) ratio
[3] $Cr^{\#}$ = atomic $Cr/(Cr+Al+Fe^{3+})$ ratio

Zircon

Zircon was found in 7 of the 10 residues investigated (only MAG-1, MRG-1, and JP-1 did not appear to possess the mineral after dissolution). In many cases, the zircon grains were euhedral or showed negligible evidence for acid attack. In addition to zirconium, the zircons contained variable amounts of hafnium (1.2 to 3.5 weight % HfO_2) and yttrium (up to 3.2 weight % Y_2O_3). Although some zircons have been shown to contain appreciable amounts of uranium, thorium, and REE, these elements were not observed in the analyzed grains. The presence of zircon in many of the samples accounts for the significantly lower zirconium and hafnium concentrations obtained for these materials after open-beaker digestions (*see* Table 36.1; *see* Figure 36.1). Tomlinson, Bowins and Hechler (1999) showed that the incomplete acid-digestion of this mineral during open-beaker digestions was responsible for negative anomalies on normalized multi-element diagrams for metamorphosed komatiitic rocks, prompting the development of the closed-beaker method at Geo Labs. The close match between the zirconium and hafnium concentrations determined after the closed-beaker digestions and the reference values for the materials analyzed confirms that the closed-beaker technique that was subsequently established at Geo Labs is adequately able to digest zircons in most sample matrices.

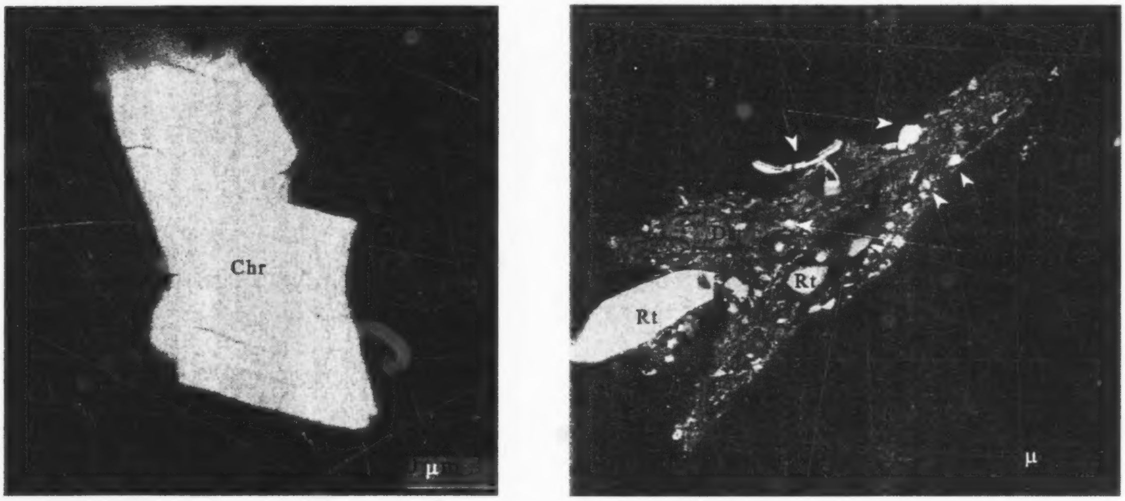

Photo 36.1. Backscattered SEM images of residues after open-beaker digestions. A) Subhedral chromite (peridotite, JP-1). B) Rutile (Rt), zircon (Zrn), and xenotime (Xen) in diaspore (Dsp) matrix (bauxite, BX-N).

SUMMARY AND IMPLICATIONS

The analyses of the solutions produced by open- and closed-beaker acid attack of a suite of reference materials and the associated residues show that most major and trace elements may be successfully analyzed in a range of different rock matrices after a relatively short acid attack in open beakers. However, the concentrations of a number of trace elements that may be important for either petrogenetic or metallogenetic studies can be underestimated when preparing samples by such techniques owing to their retention in acid-resistant minerals. Such retention may be either "active", where the element is present either in solid solution (e.g., Hf in zircon), or "passive", where the element is concentrated in discrete mineral inclusions in the insoluble mineral (e.g., xenotime, rutile, and zircon in diaspore; *see* Photo 36.1B). Where possible, the resistant minerals that controlled the trace element concentrations in each sample were characterized, along with any additional elements that may be affected.

The acid-resistance of some resistant minerals (e.g., chromite, xenotime, and zircon) may be overcome by digestion under more extreme conditions, but others (e.g., cassiterite and rutile) appear to remain insoluble under all but the most extreme conditions. Because no study was carried out on the reference materials prior to digestion, it was not possible to estimate the relative proportion of the various acid-resistant phases that may have dissolved in each of the 2 digestion techniques, and so determine either the acid-resistance of each mineral or the relative importance of the mineral to the overall budget for each element. However, from the significantly low zirconium, hafnium, tin, and chromium contents determined in many of the samples and the fresh appearance of many of the zircon, cassiterite and chromite grains after analysis, it is clear that individual accessory phases can exert a strong control on certain elements.

In order to ensure accurate and cost-effective analyses and avoid the potential effects of mineral insolubility on measured trace element concentrations, it is necessary to ensure that both the crushing and digestion techniques are adequate for the purpose. For many geochemical analyses, such problems do not arise and accurate major and trace element concentrations can be obtained by conventional crushing and open-beaker digestion methods. However, where potentially insoluble minerals may contain the trace elements of interest as principal components, minor elements in solid solution or as trace-element rich inclusions in insoluble minerals, it is essential that the samples be adequately disaggregated prior to decomposition and decomposed using more aggressive techniques. For some minerals (e.g., chromite, xenotime, or zircon), longer digestions in closed beakers can achieve complete dissolution. However, a number of minerals (e.g., cassiterite) do appear to require alternative preparation techniques in order to bring them into solution (e.g., alkali fusion or peroxide sinter of either the original sample powder, or any insoluble residue after acid dissolution). Such methods are currently under development at Geo Labs. Alternatively, if only the minor elements are required (or the trace elements of interest are present at elevated concentrations), then analyses can be carried out using X-ray fluorescence spectrometry (XRF) on pressed powder pellets.

During the investigation of the suite of 10 certified reference materials described in this article, several minerals commonly present in igneous and/or sedimentary rocks have been shown to control the measured trace element contents of the whole rocks (either actively or passively). Potential additions to this list would be aluminosilicate (kyanite, sillimanite, or andalusite), corundum, garnet, monazite, staurolite, and tourmaline, all of which have been slow to dissolve under open-beaker conditions. Owing to the potential shielding of acid-soluble trace element bearing minerals by acid-resistant phases (whether or not they contain any trace elements of interest), it is necessary to recognize and take steps to ensure the digestion of such minerals *before* analysis, or to interpret the resulting data in light of the sample mineralogy.

Further details of analytical services and methods available at Geo Labs may be obtained by contacting the Client Services Representative at 933 Ramsey Lake Rd., Sudbury, ON P3E 6B5. Tel: (705) 670 5637; toll free: 1-866-436-5227; e-mail: geoscience.labs@ndm.gov.on.ca; web site http://www.mndm.gov.on.ca/mndm/mines/labs/labintroe.htm.

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Geoscience Program Initiatives

37. Ontario Mineral Exploration Technologies (OMET) Program

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INTRODUCTION

Announced by the Ministry of Northern Development and Mines in September 2000, the Ontario Mineral Exploration Technologies (OMET) Program is a four-year, $8.0 million initiative to develop and test innovative mineral exploration technologies and methods. The goal is to enhance the efficiency of the exploration firms in high potential geological areas of Ontario. OMET is now at the end of the second quarter of the third year of operation of its four-year term. Significant progress has been achieved in the past 2 years with the approval of 13 projects for funding. The new technologies and methods developed will increase Ontario's attractiveness to mining and mineral exploration by funding high-potential projects that are targeting Ontario's mineral exploration challenges.

As at September 12, 2002, approximately $4.7 million has been awarded to projects that have undergone assessment and/or review and approval recommendation by the Expert Technical Advisory Committee (ETAC).

The most significant change to the program occurred in December 2001 when the Management Board took the decision to change the submission of proposals to a one-stage application process by removing the requirement to submit the Letter of Intent Application form. This decision created a more efficient process for review by ETAC and decision by the Management Board.

In November 2001, Wally Rayner replaced Ed Debicki as Program Coordinator. Two ETAC members resigned and were replaced in 2002.

PROPOSAL SUMMARY

The Table 37.1 summarizes the 13 approved proposals indicating the project goals and the exploration challenges being address by the researcher. More importantly, however, the third column describes the potential direct impact on the Ontario mineral exploration sector. A brief description is presented to assist in the understanding of the scope of research being carried out by the participants in the OMET program.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.37-1 to 37-5.

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Table 37.1. A summary of the proposals that have been awarded funding through OMET.

Proposal #, Name and Title	Project Goals	Exploration Challenge Addressed
P01-02-001 Camiro **Detectability of mineral deposits with airborne gravity**	To model ore deposit responses from airborne gravity data.	The challenge is to refine the target- discrimination potential of airborne gravimetry. This research will further the understanding of the expected responses of economic targets, the masking of geological noise, the detectability versus depth relationship, and the system specifications of airborne gravity instruments for detection of ore bodies.
P01-02-002 Camiro **Three dimensional surficial geochemistry**	To determine by field trials which form of metal transport is most likely to be at work for a given area. The result being lower sample densities and lower the number of test parameters.	Surficial geochemistry in areas of thick overburden cover has always present a challenge to mineral exploration. By systematically studying the natural processes at work at selected sites, the sampling effectiveness and mineral discovery rate in overburden areas will be enhanced.
P01-02-003 Camiro **The use of soil gas hydrocarbon technique to differentiate barren from ore-bearing conductors**	To use laboratory experiments to determine which organic compounds are related to which ore type. Field studies will sample "B horizon: soils over different types of conductive bodies. Comparison will be made between the controlled laboratory studies and field studies.	The challenge for explorationists is to distinguish between barren electromagnetic conductors and ore-bearing electromagnetic conductors. The project is expected to provide an effective and cost-efficient tool for locating and distinguishing between ore types.
P01-02-007b Geotech **Modeling, interpretation methods and field trial of an existing prototye AFMAG system**	To develop and test by field trials an extremely low frequency (ELFMAG) with high sensitivity multiple-frequency digital system for airborne and ground surveys.	Thick conductive overburden and Paleozoic cover rocks have presented a barrier to traditional electromagnetic methods. This method is expected to provide the capabilities to look deeper at acceptable costs. It will have the potential to map conductive bodies to depths of 1000 m.
P01-02-008a GSC **Three dimensional geochemisty in the Abitibi**	To develop and document a soil geochemical technique for the Abitibi Clay Belt to locate base metal and gold deposits.	The Abitibi Clay Belt with thick and exotic cover has resulted in costly exploration work in the area. The clarification and identification of element migration pathways and fixation in the near surface will allow explorers to locate base metal and gold mineralization through tens of metres of glacial sediments in a cost-effective manner.
P01-02-011a Ferra Dynamics **Technology development of a high bandwidth helicoper EM system**	To test a concept to triple the sample density of HEM system in order to more accurately map glacial sediments and identify conductive bodies underneath them.	Conductive sediments in many regions of Ontario have masked the electromagnetic responses of conductive ore-bearing rocks. This research project will develop, test and prove the acquisition technology so that commercial surveys may be flown using this technology. The technology will be a step toward a basis of one capable of penetrating deep clay belts.
P01-02-014 Quantec **Demonstration survey of the distributed acquisition method MT/IP earth imaging technology**	A prototype system will be demonstrated to show that it will quantitatively map lithology, structure, alteration, and mineralization. The data collected will be interpreted using 3D earth models with GoCAD.	The challenge is to demonstrate the technology in a variety of geological environments and over several control sites in northern Ontario. The technology is designed to detect mineralization to depths of 1000 m in areas of glacial cover. The new technology will be capable of mapping the bedrock geology.

Table 37.1. Continued

Proposal #, Name and Title	**Project Goals**	**Exploration Challenge Addressed**
P01-02-016a University of Ottawa **Geochemical detection of buried and disseminated palladium mineralization in northwestern Ontario**	The research will target mafic and ultramafic igneous rock complexes in the search for palladium and platinum using pathfinder elements.	A new type of platinum group metal deposits has emerged in Ontario. The challenge is to identify possible ore-bearing rocks when there is no clear geophysical signature. Commercial assaying methods are expensive with high detection limits and have limitations in targeting potential areas. The research will examine alteration, dispersion, solubility, leaching, and precipitation barriers. The result will be concepts for geochemical exploration and anomaly definition.
P01-02-018 York University **Geodata Analysis Systems (GEODAS) for mineral exploration in Ontario**	The goal of this research is to demonstrate the GeoDas methodology and feasibility to produce a state of the art GIS-based technology for predictive mineral potential mapping.	The generation of mineral exploration targets, especially in areas of thick overburden cover, has become increasingly difficult because of the highly diverse and complex data sets. GeoDas has the capability and functionality to handle this challenge.
P01-02-021 Quantec **Airborne hyperspectral surface mapping over exposed and covered mineral belts in Ontario**	This project will evaluate the capabilities of the hyperspectral sensor and software for detecting rock alteration that may be indicative of 'blind' ore deposits.	This project will address the need to be able to systematically and efficiently collect hpyerspectral data from an aircraft. The result being the demonstration of a new tool for geologic mapping and definition of new prospective terrain for mineral exploration.
P01-02-023 Mira Geoscience **3D data integration methodology and tools for in-mine and near-mine exploration**	Demonstration of new 3D data interpretation method and software through case studies, using rock property modelling, and geochemical and geophysical data to maximize success in drill hole targeting.	In areas of complex geology, the challenge is to integrate and interpret the wealth of data collected during exploration in and near mine sites. This new software will deliver an efficient and cost-effective means to carry out drill hole targeting, which will lead to successful mineral exploration and the discovery of new ore reserves.
P01-02-005b Gedex **Gedex AGG (airborne gravity gradiometer) system**	This project focusses on research, development and testing of system components of a prototype high-resolution gravity gradiometer.	Currently, the only available airborne gravity system does not have the sensitivity required for the majority of mineral deposits. The Gedex AGG system will provide rapid, airborne data collection that will hve significantly greater sensitivity and bandwidth, enabling it to find deposits that are invisible to other systems.
P02-03-025 T.C. Barrie and Associates **Geochemistry of graphitic argillites and iron formation near VMS and gold deposits**	This research project will investigate geochemical and geophysical characteristics of interflow sedimentary graphitic argillites and iron formations. The resultant signatures and mineral potential mapping will target mineral deposits undercover.	The project will provide useful databases on graphitic argillites and iron formations, it will provide new methodologies for use in geochemical exploration in area of thick glacial cover. The alteration haloes associated with ore deposits can be recognized up to 1 km from the ore deposit using this geochemical method.

PROGRAM PERFORMANCE

The program approval rate is 36% or 13 proposals out of 36 received to date. The rejection rate is 27% or 10 of 36 proposals.

The OMET program will use 3 performance measures: financial leverage, transmission of new knowledge to the public, and uptake of technology transfer. Table 37.2 lists the approved and/or funded projects as of September 12, 2002.

Table 37.2. The approved and/or funded OMET projects (as of September 12, 2002).

Proposal		OMET Award	Researcher Cash	Researcher In-kind	Cash Leverage	Total Leverage
P01-02-001	Camiro	$ 56,100	$ 56,100	$ 0	1.0	1.0
P01-02-002	Camiro	$358,975	$ 262,040	$100,000	0.73	1.01
P01-02-003	Camiro	$108,825	$ 168,825	$120,000	1.55	2.65
P01-02-007b	Geotech	$356,470	$ 207,330	$ 25,000	0.58	0.65
P01-02-008a	GSC	$592,000	$ 166,000	$489,000	0.28	1.11
P01-02-011a	Ferra Dynamics	$ 74,900	$ 39,000	$127,750	0.52	2.23
P01-02-014	Quantec	$625,500	$ 190,000	$ 71,500	0.30	0.42
P01-02-016a	University of Ottawa	$186,040	$ 38,000	$104,000	0.20	0.85
P01-02-018	York University	$331,500	$ 339,000	$175,000	1.02	1.55
P01-02-021	Quantec	$431,000	$ 60,000	$276,000	0.14	0.78
P01-02-023	Mira Geoscience	$529,000	$ 260,000	$639,000	0.49	1.70
P02-03-005b	Gedex	$800,000	$3,314,015	$363,000	4.41	4.60
P02-03-025	Barrie	$266,540	$ 7,500	$420,000	0.03	1.64
TOTALS		**$4,716,850**	**$5,107,810**	**$2,910,250**	**1.08**	**1.70**

Cumulative awards to date, including all fiscal years, assuming the projects go to completion is $4,716,850. The researcher combined cash and in-kind for the projects amounts to $8,018,060.

Performance Measure 1: Financial leverage
Target: $0.25 from researcher for each OMET $1.00
Actual: Each OMET $1.00 levers $1.08 researcher cash or $1.70 researchers cash plus in-kind.
Note: Leverage indicates the projects are supported by industry, universities and other governments.

Performance Measure 2: Transmission of new knowledge to public
Target: 1 Transmission per project per year
Actual: One project (P01-02-001) has been competed. This final report has been circulated to the Expert Technical Advisory Committee for their review. This project will result in a new OMET proposal (phase II) to be submitted as a result of industry–sponsor interest. The projects will not create presentation posters, or technical presentations until the results of the research are compiled; typically this occurs near the end of the project, but before the final report. Expect transmissions to be well underway by the end of December 2002.

Performance Measure 3: Uptake of technology transfer
Target: 1 receptor per funded project
Actual: This is too early to measure because only 1 project is complete. It is not possible to measure the technology uptake until the results of the project have been published. Many projects have proprietary information, which will be held in confidence for one year after completion of the project. However,

about 20 different private companies have sponsored and co-funded the OMET-funded projects. In some instances, the companies are benefitting from the testing of prototypes of the new technology as demonstration projects. This indicates that the private sector strongly supports the technical merit and mineral exploration relevance of these research projects, so uptake is not anticipated to be an issue.

CONTACT INFORMATION

Information about the OMET Program or assistance in completing the application form can be obtained from the OMET Program Office, by contacting the OMET Program Coordinator or the OMET Administrative Assistance:

- OMET Program Office
  Ontario Mineral Exploration Technologies (OMET) Program
  Mineral Exploration Research Centre (MERC)
  Willet Green Miller Centre
  B8-933 Ramsay Lake Road
  Sudbury, ON P3E 6B5
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38. Project Unit 99-315. Operation Treasure Hunt Update: Lake Sediment Geochemistry, Indicator Minerals and Industrial Minerals

R. Dyer and V. Felix

Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

Under the Operation Treasure Hunt (OTH) initiative, the Sedimentary Geoscience Section (SGS) oversaw the completion of a series of surficial media geochemistry, indicator mineral program and industrial mineral projects. The program involved completion of a series of high-density lake sediment sampling, medium-density modern alluvium (river) sampling, and industrial mineral studies concerning mica and bedrock aggregates. Field work for all of the studies was completed between 1999 and fall of 2001.

PUBLISHED REPORTS AND DATASETS

Table 38.1 contains a listing of the Open File Reports (OFRs) and Miscellaneous Release—Data (MRDs: digital data) released under the auspices of the SGS OTH program between 2000 and 2002. A total of 15 OFRs and MRDs relating to lake sediment geochemistry and 4 OFRs and MRDs pertaining to indicator minerals have been released as of October 2002. Table 38.2 lists the OTH reports and data sets that are expected to be released in 2003.

In addition, OFRs containing the results of a white mica study over Grenville Province rocks and a bedrock aggregate study for the north shore of Lake Superior have been completed and released.

RESULTS AND SUCCESS TRACKING

To date, over 388 significant discrete multi-site and/or multi-element anomalous areas have been delineated by the OTH lake sediment program and described in 15 Open File Reports. The most recent releases, Lac des Iles – Black Sturgeon River lake sediment survey and Perrault Falls area lake sediment survey, were not included in this figure.

In excess of 30 000 claim units have been staked as a direct result of the published datasets. The OGS is also aware of several property transactions that have occurred as a direct result of these surveys. The OGS will continue to follow and track such success stories (e.g., Churchill et al. 2000; Churchill et al. 2001). The publication of the reports and datasets for the projects listed in Table 38.2 during 2003 will undoubtedly increase the number of significant anomalies and result in further claim staking and exploration activity.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.38-1 to 38-5.

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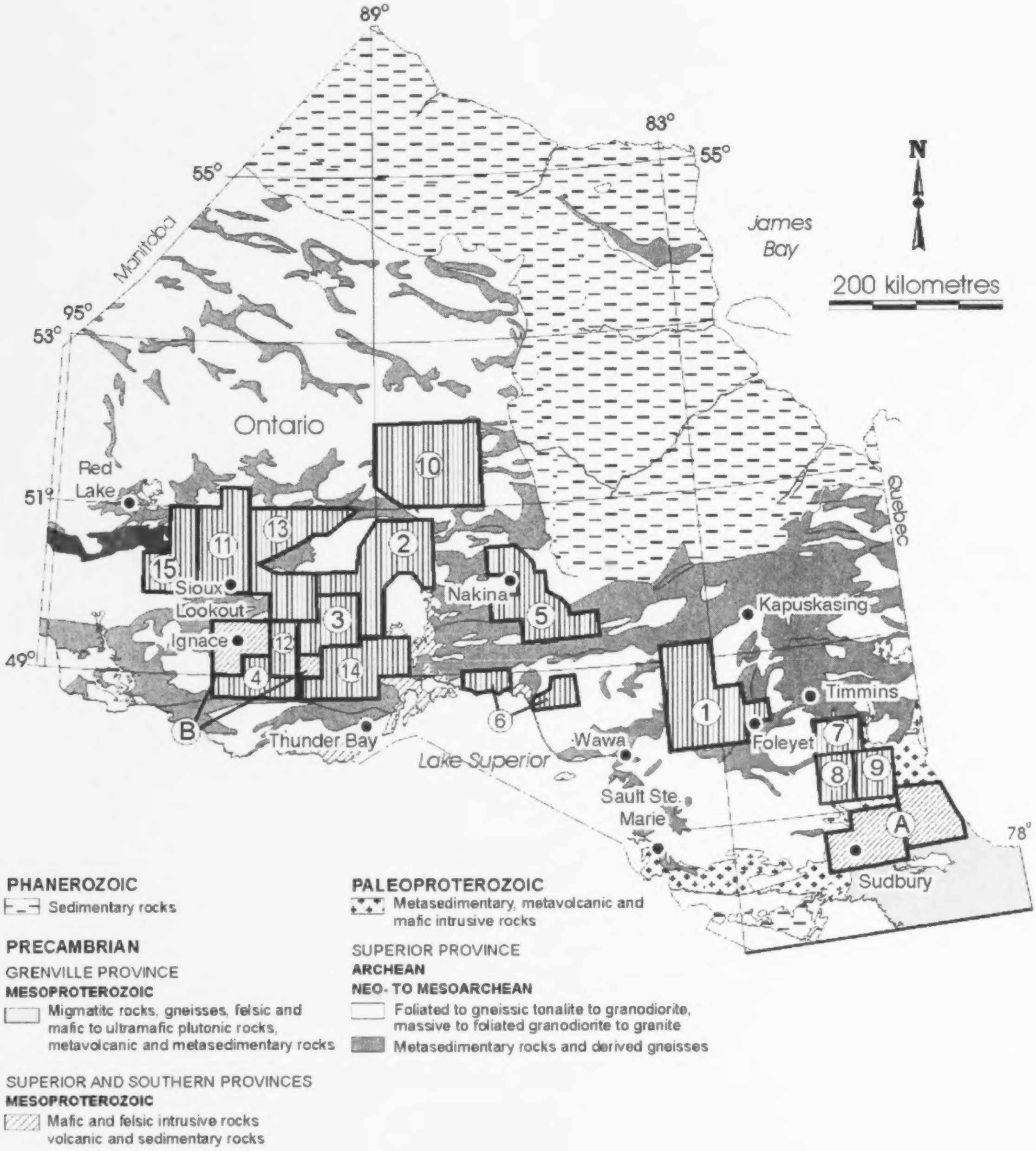
89°
83°
55°
55°
James Bay
N
200 kilometres
Manitoba
95°
53°
Ontario
Red Lake
51°
10
11
13
15
2
Sioux Lookout
Nakina
3
5
Kapuskasing
Quebec
Ignace
12
49°
4
14
B
Thunder Bay
6
Wawa
Lake Superior
1
Timmins
Foleyet
7
8
9
Sault Ste. Marie
A
78°
Sudbury
PHANEROZOIC
Sedimentary rocks
PRECAMBRIAN
GRENVILLE PROVINCE
MESOPROTEROZOIC
Migmatitc rocks, gneisses, felsic and mafic to ultramafic plutonic rocks, metavolcanic and metasedimentary rocks
SUPERIOR AND SOUTHERN PROVINCES
MESOPROTEROZOIC
Mafic and felsic intrusive rocks volcanic and sedimentary rocks
PALEOPROTEROZOIC
Metasedimentary, metavolcanic and mafic intrusive rocks
SUPERIOR PROVINCE
ARCHEAN
NEO- TO MESOARCHEAN
Foliated to gneissic tonalite to granodiorite, massive to foliated granodiorite to granite
Metasedimentary rocks and derived gneisses

Figure 38.1. Location of Operation Treasure Hunt lake sediment surveys completed and those expected to be released in 2003. Numbers and letters in boxes correspond to the projects outlined in Tables 38.1 and 38.2.

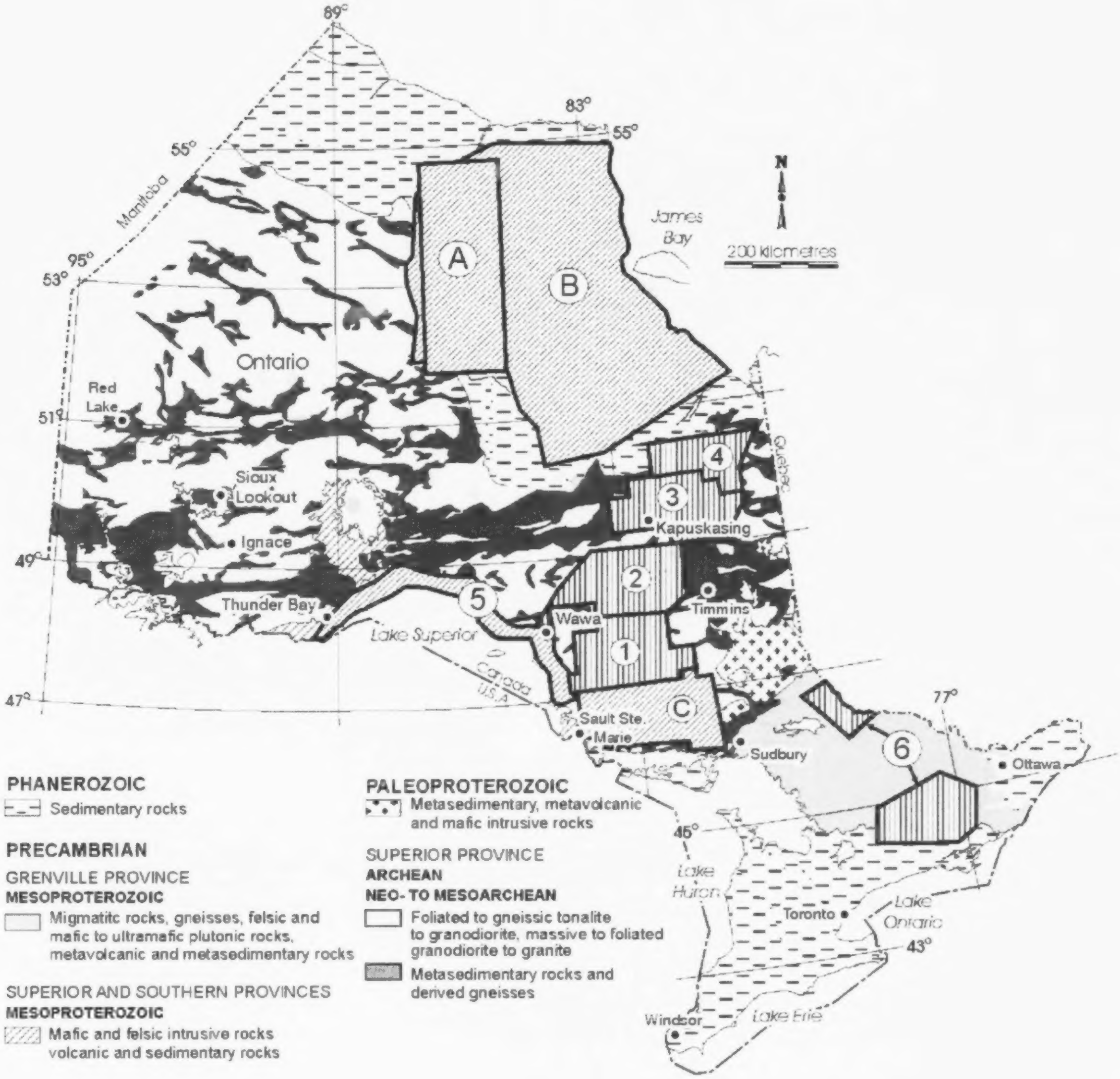
89°
83°
55°
55°
Manitoba
95°
53°
James Bay
N
200 kilometres
A
B
Ontario
Red Lake
51°
Sioux Lookout
Ignace
49°
Thunder Bay
Lake Superior
Wawa
Kapuskasing
Timmins
Quebec
1
2
3
4
5
6
C
Canada
U.S.A.
47°
Sault Ste. Marie
Sudbury
77°
Ottawa
45°
Lake Huron
Toronto
Lake Ontario
43°
Windsor
Lake Erie
PHANEROZOIC
Sedimentary rocks
PRECAMBRIAN
GRENVILLE PROVINCE
MESOPROTEROZOIC
Migmatitc rocks, gneisses, felsic and mafic to ultramafic plutonic rocks, metavolcanic and metasedimentary rocks
SUPERIOR AND SOUTHERN PROVINCES
MESOPROTEROZOIC
Mafic and felsic intrusive rocks volcanic and sedimentary rocks
PALEOPROTEROZOIC
Metasedimentary, metavolcanic and mafic intrusive rocks
SUPERIOR PROVINCE
ARCHEAN
NEO- TO MESOARCHEAN
Foliated to gneissic tonalite to granodiorite, massive to foliated granodiorite to granite
Metasedimentary rocks and derived gneisses

Figure 38.2. Location of Operation Treasure Hunt modern alluvium (KIM indicator) surveys and industrial mineral studies completed and those expected to be released in 2003. Letters and numbers in boxes correspond to projects detailed in Tables 38.1 and 38.2.

Table 38.1. Operation Treasure Hunt Open File Reports and Miscellaneous Release—Data (MRDs) for 2000–2002. Numbers 1 to 15 and 1 to 6 correspond to areas indicated on Figures 38.1 and 38.2, respectively.

	Report/MRD Number	Title: Lake Sediment Surveys	Author(s)	Year Released
1	OFR 6014 & MRD 54	Foleyet–Missinaibi area lake sediment survey: Operation Treasure Hunt	OGS (R. Dyer)	April 2000
2	OFR 6027 & MRD 56	Armstrong – Lake Nipigon area lake sediment survey: Operation Treasure Hunt	OGS (R. Dyer)	Sept 2000
3	OFR 6028 & MRD 57	Garden–Obonga Lake area lake sediment survey: gold and PGE data	OGS (J. Jackson)	July 2000
4	OFR 6034 & MRD 63	Atikokan area lake sediment survey: Au and PGEs—Operation Treasure Hunt	OGS (C. Searcy)	Dec 2000
5	OFR 6035 & MRD 64	Nakina–Longlac area lake sediment survey: Operation Treasure Hunt	OGS (R. Dyer)	Dec 2000
6	OFR 6036 & MRD 65	Schreiber–Hemlo area lake sediment survey: gold and PGE data—Operation Treasure Hunt	OGS (D. Russell)	Dec 2000
7	OFR 6053 & MRD 70	Peterlong Lake – Radisson Lake area lake sediment survey: Au and PGE data—Operation Treasure Hunt.	OGS (D. Russell)	April 2001
8	OFR 6061 & MRD 80	Montreal River headwaters area lake sediment survey, northern Ontario: gold and PGE data—Operation Treasure Hunt	OGS (J. Jackson)	July 2001
9	OFR 6062 & MRD 81	Shining Tree area high density regional lake sediment and water geochemical survey, northeastern Ontario	D. Russell and S.M. Hamilton	July 2001
10	OFR 6071 & MRD 89	Fort Hope area high density regional lake sediment geochemical survey, northwestern Ontario	OGS (J. Jackson)	Dec 2001
11	OFR 6069 & MRD 88	Sioux Lookout – Bamaji Lake area lake sediment survey: Operation Treasure Hunt	OGS (D. Russell)	Dec 2001
12	OFR 6076 & MRD 98	Wawang Lake – English River lake sediment survey, northwestern Ontario:PGE data and final results/interpretation of lake sediment geochemistry	R. Dyer	March 2002
13	OFR 6087& MRD 104	Sturgeon Lake – Lake St. Joseph area lake sediment survey: Operation Treasure Hunt	D. Russell and J. Jackson	June 2002
14	OFR 6096& MRD 108	Lac des Iles – Black Sturgeon River lake sediment survey: Operation Treasure Hunt	R. Dyer and D. Russell	Sept 2002
15	OFR 6092& MRD 106	Perrault Falls area lake sediment survey: Operation Treasure Hunt	OGS (J. Jackson)	Oct 2002

	Report/MRD Number	Title: Modern Alluvium (KIM Indicators) and Industrial Mineral Reports	Author(s)	Year Released
1	OFR 6044 & MRD 68	Results of modern alluvium sampling, Kapuskasing–Fraserdale area, northeastern Ontario: Operation Treasure Hunt – Kapuskasing Structural Zone (KSZ)	OGS (N. Tardif)	April 2001
2	OFR 6063 & MRD 82	Results of modern alluvium sampling, Chapleau area, northeastern Ontario: Operation Treasure Hunt – KSZ	OGS (N. Tardif and D. Crabtree)	July 2001
3	OFR 6065 & MRD 83	Results of modern alluvium sampling, Foleyet area, northeastern Ontario: Operation Treasure Hunt – KSZ	OGS (D. Crabtree)	Sept 2001
4	OFR 6068 & MRD 87	Results of modern alluvium sampling, Coral Rapids area, northeastern Ontario: Operation Treasure Hunt – KSZ	OGS (D. Crabtree)	Dec 2001
5	OFR 6072	Physical evaluation and assessment of bedrock aggregate resource potential, north shore of Lake Superior	Jagger Hims Ltd., Clayton Research Ltd. and Agritrans Ltd.	Dec 2001
6	OFR 6086	Industrial mineral assessment and sampling of mica in central and eastern Ontario	Watts, Griffis and McOuat and OGS	Aug 2002

Table 38.2. Operation Treasure Hunt reports and/or data sets expected to be released in 2003.

(*see* Figure 38.1)	**Project: Lake Sediment Surveys**	**Survey Type**	**Projected Release Date**
A	Sudbury–Temagami area lake sediment survey, northeastern Ontario	High density lake sediment	January 2003
B	Ignace area lake sediment survey, northwestern Ontario	High density lake sediment	March 2003
1	Re-analysis for PGEs in lake sediment, Foleyet–Missinaibi area (OTH area A), northeastern Ontario	Re-analysis for PGEs	April 2003

(*see* Figure 38.2)	**Project: Modern Alluvium (KIM indicators)**	**Survey Type**	**Projected Release Date**
A	Heavy mineral – geochemical survey of the upper reaches of the Winiskisis Channel, Ekwan and Attawapiskat River area (Spider 3), northern Ontario	Indicator minerals and fine fraction geochemistry	Early 2003
B	Preliminary release of estimated KIM indicator grain counts, James Bay Lowland	Indicator minerals	Early 2003
C	Results of modern alluvium sampling, Sault Ste. Marie – Espanola area, northeastern Ontario	Indicator minerals	Early 2003

REFERENCES

Churchill, L.L., Roque, J., Baker, C. and Fyon, A. 2000. Preliminary impact analysis of Operation Treasure Hunt surveys; *in* Summary of Field Work and Other Activities 2000, Ontario Geological Survey, Open File Report 6032, p.48-1 to 48-10.

Churchill, L.L., Fyon, J.A. and Baker, C.L. 2001. Measuring the results of Ontario Geological Survey projects; *in* Summary of Field Work and Other Activities 2001, Ontario Geological Survey, Open File Report 6070, p.3-1 to 3-11.

39. Project Unit 01-306. Sedimentary Geoscience Observations Database Project 2002

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INTRODUCTION

Over the years, the Sedimentary Geoscience Section (SGS) has generated large volumes of project-related data, including lake sediment and lake water geochemistry, indicator mineral data and overburden geochemistry. To meet increasing demand from clients for easily accessible data in a digital format, the Sedimentary Geoscience Observations (SGO) database project was launched.

The SGO data are stored on a database server located at the Ministry of Northern Development and Mines (MNDM) in Sudbury. It is also anticipated that the data will reside in the Internet-accessible Land Information Ontario (LIO) data warehouse (Land Information Ontario 2002).

In 2001, data analysis for this project was completed, and a database was constructed for use in converting and bringing together data (van Haaften et al. 2001). From December 2001 onward, a private vendor was contracted by MNDM to bring existing data into the SGO database, with expected completion of 48 data sets by the fall of 2002. Work is also under way to enable public access to the data.

INDIVIDUAL DATA SETS

MNDM's SGO data are available as "Miscellaneous Release—Data" (MRD) publications, each composed of a CD-ROM or floppy disk(s). The data organization within MRDs varies significantly as a result of changing methodologies and scientific advances over time. The data sets fall into 2 main groups, surficial geochemistry surveys and indicator mineral surveys, and some data sets include both kinds of data. MRD data sets are used in conjunction with hard-copy geoscientific reports, which are also published by MNDM. These reports contain survey details and other important metadata.

The various data types are illustrated using the following MRD data sets:

- MRD 31, "Lake sediment and water geochemical data from a survey of 32 townships in the Montreal River headwaters area, centred on Gowganda, Ontario" by Hamilton (1997) and;
- MRD 34, "Heavy mineral database derived from overburden, for kimberlite, massive magmatic sulfides and gold, Kapuskasing area, northeastern Ontario" by Morris (1998).

Table 39.1 lists the data files from MRD 31 and MRD 34, and Table 39.2 provides examples of the data sets.

Summary of Field Work and Other Activities 2002,
Ontario Geological Survey, Open File Report 6100, p.39-1 to 39-6.

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Table 39.1. List of data files from lake sediment MRD 31 and indicator mineral MRD 34.

Data Files of Lake Sediment MRD 31

File Name	Size (Kbytes)	Description
Mrd31.exe	1,112	self-extracting compressed zip archive file
Zipread.me	2	documentation file explaining how to uncompress the data
Readme.txt*	5	documentation file explaining the data files
Mh-sed.wk1*	1,204	field and laboratory data for 1172 lake sediment samples
Mh-sedqc.wk1*	228	data for quality control samples submitted with the unknowns
Mh-wat.wk1*	1,349	field and laboratory data for 1336 lake water samples
Mh-watqc.wk1*	1,112	data for quality control samples submitted with the unknowns

Data Files of Indicator Mineral MRD 34

File Name	Size (Kbytes)	Description
Mrd34xls.exe	649	self-extracting compressed zip archive file of Microsoft Excel data
Mrd34txt.exe	163	self-extracting compressed zip archive file of ASCII data
Zipread.me	1	documentation file explaining how to uncompress the data
Kapintro.xls*	24	definitions and abbreviations used in the data files
Kapappa.xls*	138	sample site locations
Kapappb.xls*	55	pebble data summary
Kapappc.xls*	51	sample processing data
Kapappd.xls*	43	detailed gold grain summary
Kapappe.xls*	60	summary of kimberlite indicator mineral (KIM) counts
Kapappf.xls*	63	summary of metamorphic/massive magmatic sulphide indicator minerals (MMSIM® [4]) counts
Kapappg.xls*	910	summary of microprobe data for KIMs
Kapapph.xls*	52	summary of microprobe data for gahnite
Kapappi.xls*	63	heavy mineral picking remarks

* indicates a file extracted from the archive files

BRINGING INDIVIDUAL DATA SETS INTO THE SEDIMENTARY GEOSCIENCE OBSERVATIONS DATABASE

The source data had to be loaded into the SGO database structure as shown in Figure 39-1. The database was initially built and tested in Microsoft Access, and MNDM's Business Solutions Section used Bunker Hill Scriptoria software to convert the Access database to Oracle. The data conversion contractor maintained and "grew" this Oracle database at their site, and periodically delivered complete data dumps to MNDM. Business Solutions Section loaded the data dumps into their database server, and Sedimentary Geoscience Section staff accessed the Oracle database across the network with Microsoft Access and ODBC to perform final quality assurance on the converted data.

The variable organization of the MRD data made it impractical to write a data import program. Instead, the data conversion contractor used Microsoft Excel and Access software interactively to convert the source data into individual SGO-structured Access databases, one for each MRD data set. The contractor sent the individual MRD Access databases to MNDM for quality assurance checks, then made requested corrections and loaded each MRD Access database into Oracle.

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[4] MMSIM is a registered trademark of Overburden Drilling Management Limited, Nepean, Ontario.

Table 39.2. Examples of data files from MRD 31 and MRD 34.

Part of Data File Mh-sed.wk1 from Lake Sediment MRD 31

Sample	Eastings	Northings	Sediment Composition	Sediment Colour	Sediment maturity	Ag-ms	Al-ms	B-ms
1	525170	5280008	none	med. brown	5	0.328	13462.64	10.012
2	524742	5280641	none	med. brown	5	0.344	13985.49	8.618
3	516469	5276287	none	med. brown	5	0.128	12904.27	3.119
4	515215	5278432	none	med. brown	5	0.138	13551.04	3.932
5	515541	5276926	none	med. brown	5	0.154	14687.88	3.575
6	515914	5275558	none	med. brown	5	0.144	15026.76	3.405
7	515920	5274549	none	med. brown	5	0.16	13377.47	3.713
8	516487	5274958	none	med. brown	5	0.095	10750.63	2.36
9	513831	5277238	sandy	med. brown	4	0.325	11761.01	4.056
11	514527	5275325	none	dark green	5	0.324	15267.87	3.738
12	514718	5274099	none	dark green	5	0.373	15864.95	6.793
13	515251	5271032	none	dark green	5	0.249	13613.57	4.867
14	515750	5272100	none	dark green	5	0.23	12985.98	5.523
15	533810	5288693	none	med. green	4	0.133	13990.06	1.734

Part of Gold Grain Data File Kapappd.xls from Indicator Mineral MRD 34

SAMPLE No.	PANNED Y/N	DIAMETER	THICKNESS	NUMBER OF GRAINS						TOTAL
				RESHAPED		MODIFIED		PRISTINE		
				T	P	T	P	T	P	
001-Tm-97	N	50 x 50	10 C	1						1
			Totals:	1						1
003-Ma-97	N	50 x 75	13 C	1						1
		525 x 775	94 C	1						1
			Totals:	2						2
010-Tm-97	N	25 x 25	5 C	1						1
			Totals:	1						1
019-Tm-97	N	50 x 275	31 C			1				1
			Totals:			1				1
023-Ma-97	N	75 x 100	18 C			1				1
			Totals:			1				1

Part of Mineral Grain Chemistry File Kapappg.xls from Indicator Mineral MRD 34

Sample	SiO2	TiO2	Al2O3	Cr2O3	MgO	CaO	MnO	FeO	NiO
Almandine Garnet									
043-TM-1	39.01	0.03	22.06	0.01	10.95	0.97	0.61	26.68	0.00
043-TM-2	38.76	0.01	22.04	0.09	9.72	1.07	0.60	28.47	0.00
043-TM-3	38.72	0.03	22.01	0.00	9.54	1.03	0.58	28.40	0.00
043-TM-4	38.78	0.02	21.80	0.00	9.79	1.77	0.64	27.17	0.01
043-TM-5	38.42	0.02	21.80	0.01	8.00	2.07	0.90	29.03	0.00
043-TM-6	38.81	0.01	21.76	0.06	9.62	2.93	0.41	25.91	0.00
043-TM-7	38.19	0.00	21.73	0.06	8.15	0.92	0.74	30.00	0.00
043-TM-8	38.43	0.02	21.71	0.11	8.31	2.26	0.91	28.15	0.00
122-MA-1	39.02	0.02	21.93	0.10	9.83	3.64	0.56	25.76	0.00
122-MA-2	37.65	0.03	21.32	0.03	4.77	1.50	2.30	33.70	0.04

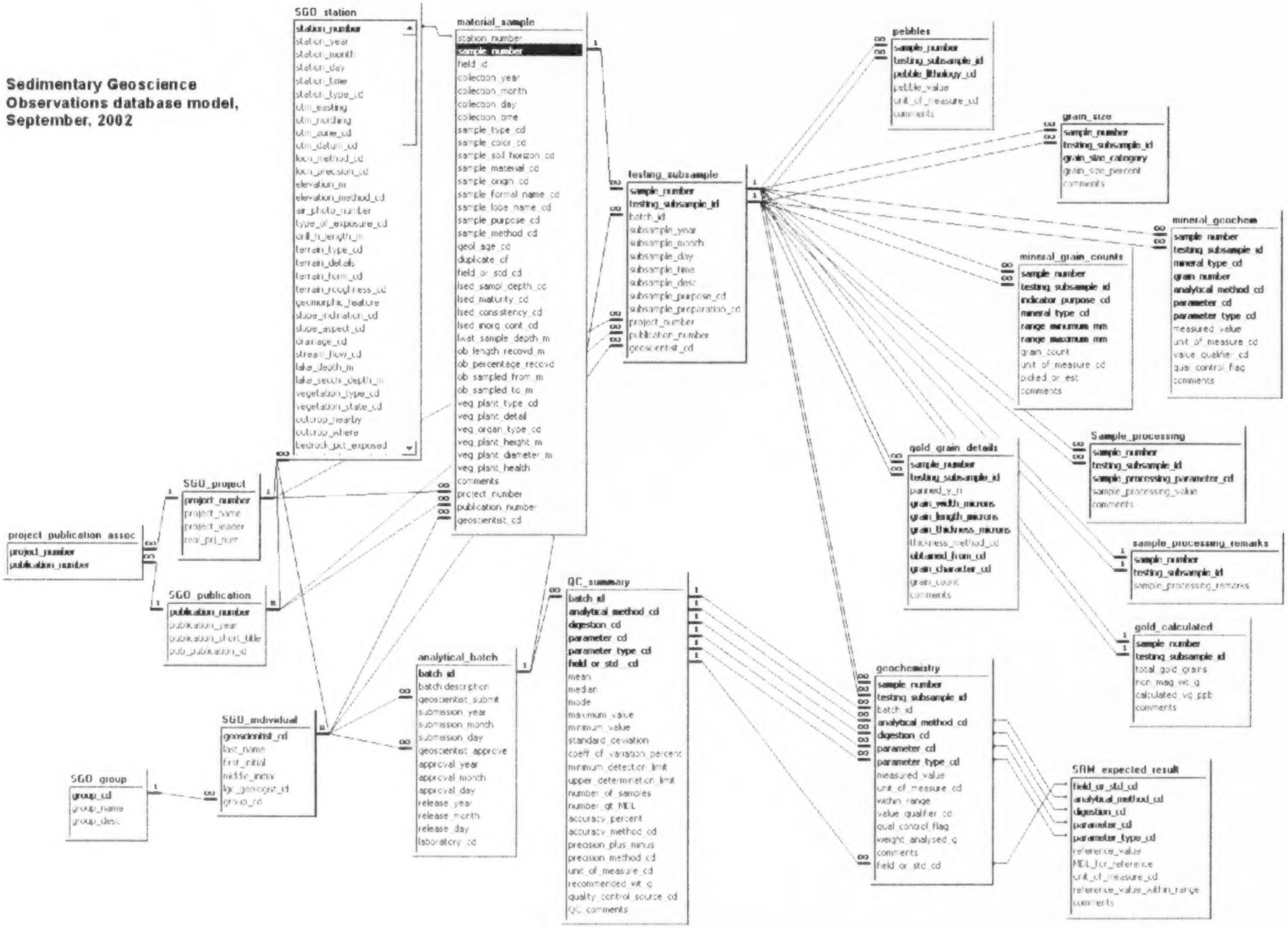
Sedimentary Geoscience Observations database model, September, 2002
SGO_station
station_number
station_year
station_month
station_day
station_time
station_type_cd
utm_easting
utm_northing
utm_zone_cd
utm_datum_cd
locn_method_cd
locn_precision_cd
elevation_m
elevation_method_cd
air_photo_number
type_of_exposure_cd
drill_h_length_m
terrain_type_cd
terrain_details
terrain_form_cd
terrain_roughness_cd
geomorphic_feature
slope_inclination_cd
slope_aspect_cd
drainage_cd
stream_flow_cd
lake_depth_m
lake_secchi_depth_m
vegetation_type_cd
vegetation_state_cd
outcrop_nearby
outcrop_where
bedrock_pct_exposed
material_sample
station_number
sample_number
field_id
collection_year
collection_month
collection_day
collection_time
sample_type_cd
sample_color_cd
sample_soil_horizon_cd
sample_material_cd
sample_origin_cd
sample_formal_name_cd
sample_lobe_name_cd
sample_purpose_cd
sample_method_cd
geol_age_cd
duplicate_of
field_or_std_cd
lsed_sampl_depth_cd
lsed_maturity_cd
lsed_consistency_cd
lsed_inorg_cont_cd
lwat_sample_depth_m
ob_length_recovd_m
ob_percentage_recovd
ob_sampled_from_m
ob_sampled_to_m
veg_plant_type_cd
veg_plant_detail
veg_organ_type_cd
veg_plant_height_m
veg_plant_diameter_m
veg_plant_health
comments
project_number
publication_number
geoscientist_cd
testing_subsample
sample_number
testing_subsample_id
batch_id
subsample_year
subsample_month
subsample_day
subsample_time
subsample_desc
subsample_purpose_cd
subsample_preparation_cd
project_number
publication_number
geoscientist_cd
pebbles
sample_number
testing_subsample_id
pebble_lithology_cd
pebble_value
unit_of_measure_cd
comments
grain_size
sample_number
testing_subsample_id
grain_size_category
grain_size_percent
comments
mineral_geochem
sample_number
testing_subsample_id
mineral_type_cd
grain_number
analytical_method_cd
parameter_cd
parameter_type_cd
measured_value
unit_of_measure_cd
value_qualifier_cd
qual_control_flag
comments
mineral_grain_counts
sample_number
testing_subsample_id
indicator_purpose_cd
mineral_type_cd
range_minimum_mm
range_maximum_mm
grain_count
unit_of_measure_cd
picked_or_est
comments
Sample_processing
sample_number
testing_subsample_id
sample_processing_parameter_cd
sample_processing_value
comments
gold_grain_details
sample_number
testing_subsample_id
panned_y_n
grain_width_microns
grain_length_microns
grain_thickness_microns
thickness_method_cd
obtained_from_cd
grain_character_cd
grain_count
comments
sample_processing_remarks
sample_number
testing_subsample_id
sample_processing_remarks
gold_calculated
sample_number
testing_subsample_id
total_gold_grains
non_mag_wt_g
calculated_vg_ppb
comments
geochemistry
sample_number
testing_subsample_id
batch_id
analytical_method_cd
digestion_cd
parameter_cd
parameter_type_cd
measured_value
unit_of_measure_cd
within_range
value_qualifier_cd
qual_control_flag
weight_analysed_g
comments
field_or_std_cd
SRM_expected_result
field_or_std_cd
analytical_method_cd
digestion_cd
parameter_cd
parameter_type_cd
reference_value
MDL_for_reference
unit_of_measure_cd
reference_value_within_range
comments
QC_summary
batch_id
analytical_method_cd
digestion_cd
parameter_cd
parameter_type_cd
field_or_std_cd
mean
median
mode
maximum_value
minimum_value
standard_deviation
coeff_of_variation_percent
minimum_detection_limit
upper_determination_limit
number_of_samples
number_gt_MDL
accuracy_percent
accuracy_method_cd
precision_plus_minus
precision_method_cd
unit_of_measure_cd
recommended_wt_g
quality_control_source_cd
QC_comments
analytical_batch
batch_id
batch_description
geoscientist_submit
submission_year
submission_month
submission_day
geoscientist_approve
approval_year
approval_month
approval_day
release_year
release_month
release_day
laboratory_cd
SGO_project
project_number
project_name
project_leader
real_prj_num
project_publication_assoc
project_number
publication_number
SGO_publication
publication_number
publication_year
publication_short_title
pub_publication_id
SGO_individual
geoscientist_cd
last_name
first_initial
middle_initial
lgc_geologist_id
group_cd
SGO_group
group_cd
group_name
group_desc

Figure 39.1. Sedimentary Geoscience Observations database structure.

In test loading of MRD spreadsheets to the SGO database, MNDM developed and used the following methodology. Individual data spreadsheets were cleaned up using Excel; for example, column headings were converted to single rows where necessary and spreadsheet cells with text strings representing null were replaced with empty cells. The cleaned-up spreadsheets were brought into Access as tables, and empty columns from SGO tables where the data would reside were added to the imported data tables. These new columns were filled with necessary values and constants using update queries. The data were then appended to staging tables and subsequently to the SGO database. During testing, the SGO database resided in the same Access file as the import tables and staging tables, however, in future MNDM data loading, the final appends will be done to ODBC-linked tables of an Oracle SGO database. This data loading methodology, with modifications, was used by the data loading contractor.

DATA LOADING STATUS

To date, 48 MRD data sets have been slated for conversion and import to the SGO database, with completion expected in the fall of 2002. The database is proving to be quite large. In September 2002, with 42 MRDs loaded, the database contained 2.7 million geochemical analyses, 68 000 samples, 35 000 sampling locations (stations) and a large amount of other data.

In September 2002, 68 published MRDs existed that could go into SGO. With 48 data sets already slated for conversion, that leaves 20 more data sets that are also potentially available for loading. The OGS regularly releases this type of data, so adding data into the SGO database will be an ongoing task. Also, the data conversion and related quality assurance processes have identified data maintenance issues that may be addressed over time. MNDM intends to carefully assess the quality of the initial database containing 48 MRDs, and will then decide how to proceed with further data conversions into the SGO database.

ENABLING DATA ACCESS

Two approaches are being discussed for enabling public access to the SGO data:

- direct distribution of digital data files
    - MRD data sets are already available for purchase.
    - Custom queries of data from the SGO database may be offered.
    - Possibly the entire database may be offered for purchase.
- Internet access to the data
    - It is also anticipated that the SGO data will be loaded into the Land Information Ontario (LIO) data warehouse. Data will be accessed through MNDM's Earth Resources and Mineral Exploration Website (ERMES) and LIO. This approach may follow that of the existing lithogeochemistry application within ERMES–LIO. It may allow on-line plotting of sample locations, inspection of data related to point locations and simple queries of data.
    - The federal government sponsors CGKN, the Canadian Geoscience Knowledge Network. CGKN has developed a graphical Internet application for displaying geochemical data as proportional dots in a map view. Currently discussions are under way to explore whether CGKN may play a role in Internet enabling of Ontario's SGO data.

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Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
LENGTH					
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
AREA					
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
VOLUME					
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
CAPACITY					
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
MASS					
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
CONCENTRATION					
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

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